Jet Results from DØ

and a little bit of background

Defining, measuring, and interpreting jet final states in hadron collisions

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Multijet (n>2) measurements
Double Parton Interactions
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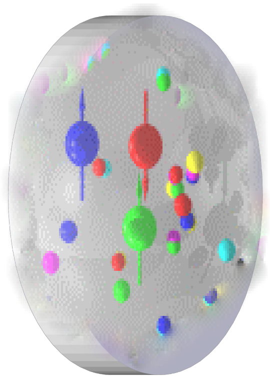
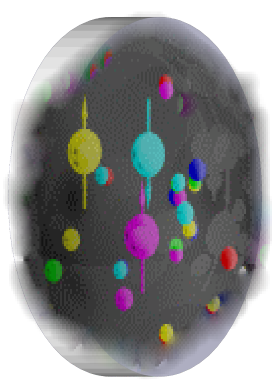
Determination of alpha_s

$P\bar{P}$ collisions and jet production

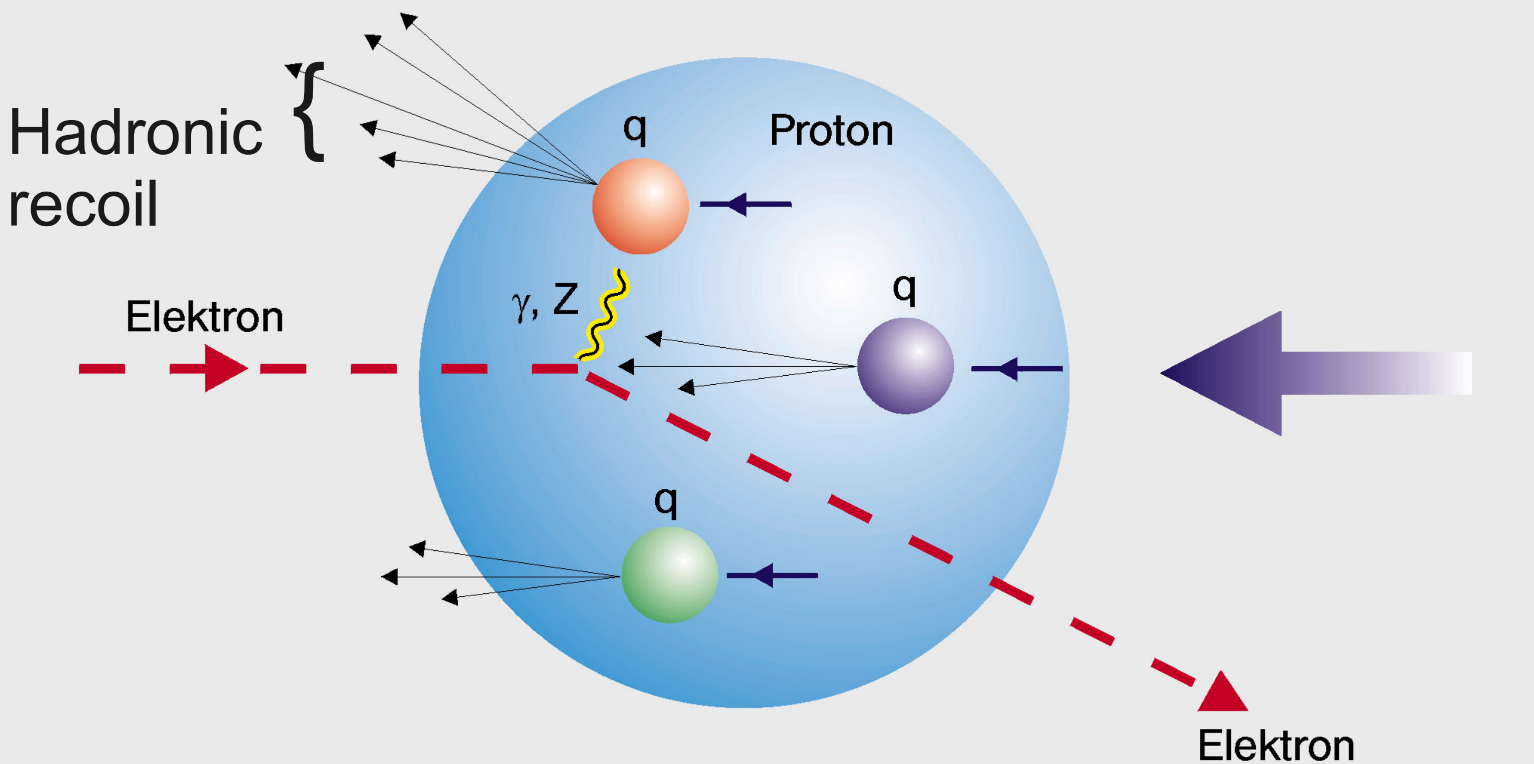
The initial state





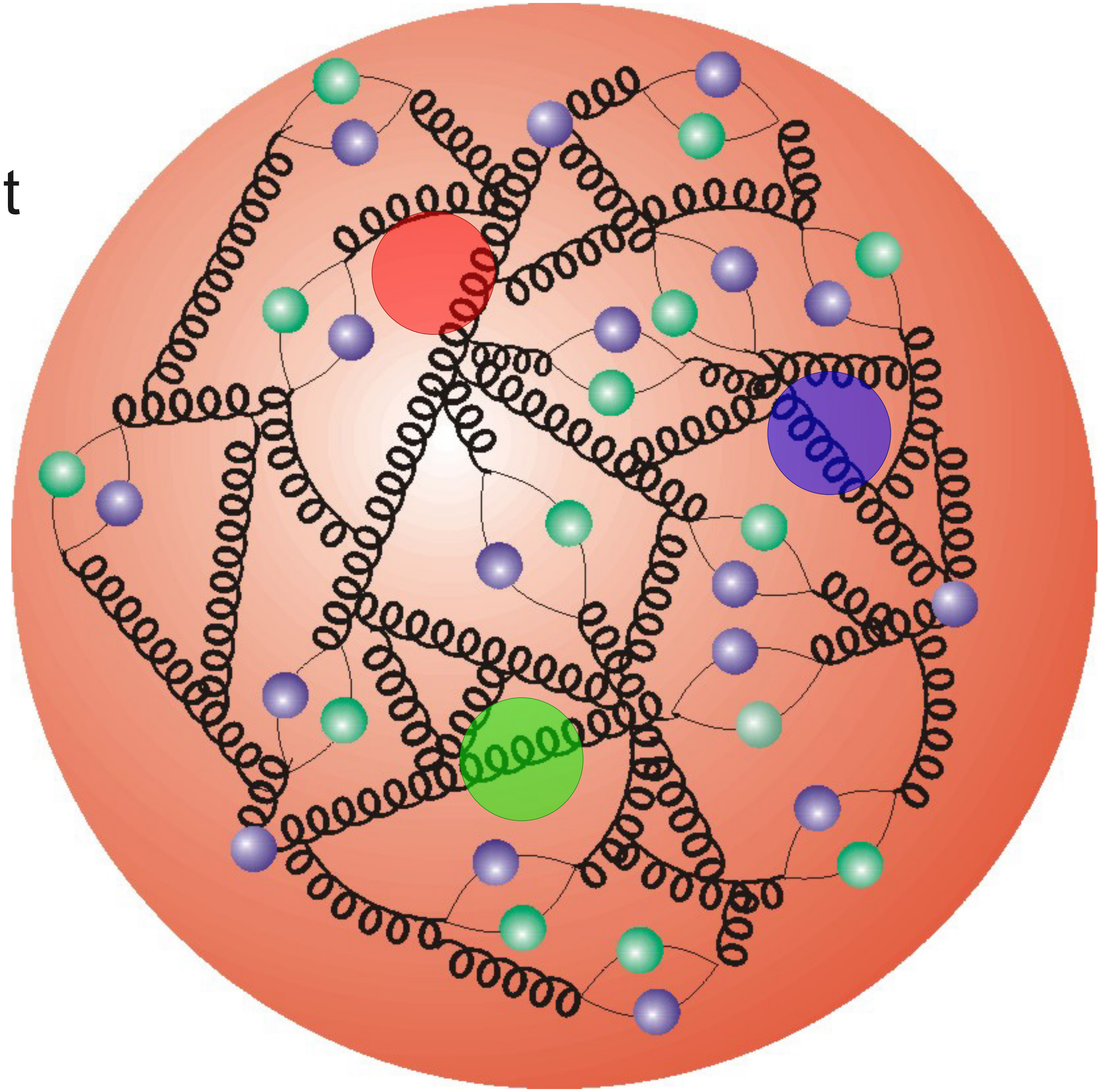
Non-perturbative parton distribution functions (PDFs) give initial parton states. Determined empirically.

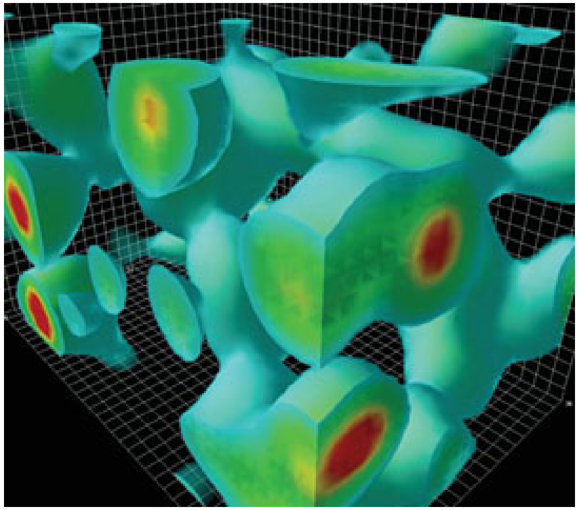
e.g. Deep inelastic scattering to probe proton structure



Initial state

Hadron structure is rather fluid. The harder you look, the more you see. Valence quarks account for ~few percent of proton's mass. The rest is due to QCD interactions, creating a sea of partons of incredible complexity





$-\Delta p^2$

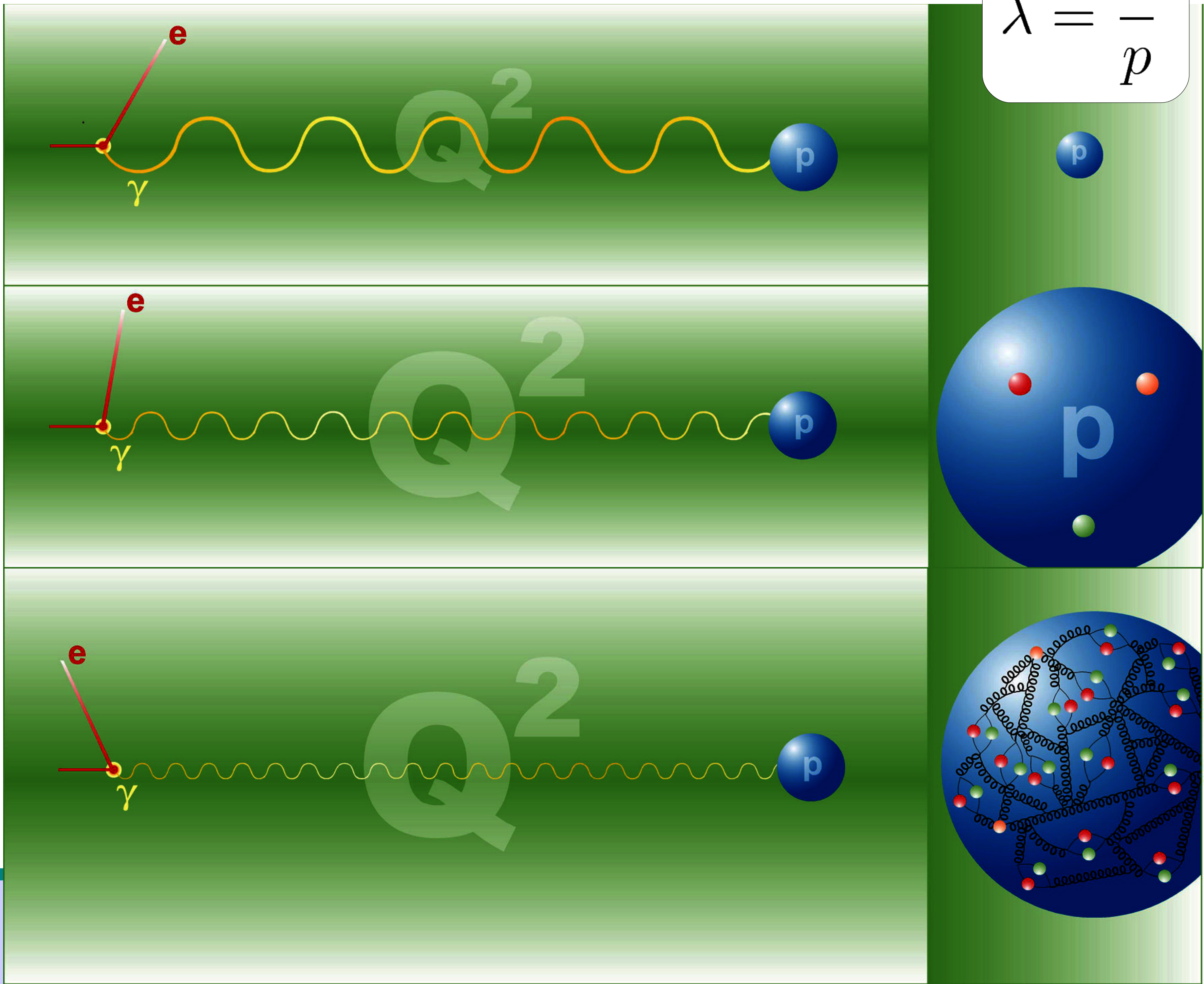
Q^2 = level of magnification

$$\lambda = \frac{h}{p}$$

High momentum probes needed to resolve small features.

- Observable initial state is effectively a function of momentum exchange.

- Lower momenta probes integrate over *smaller* (Δx,Δt) features.



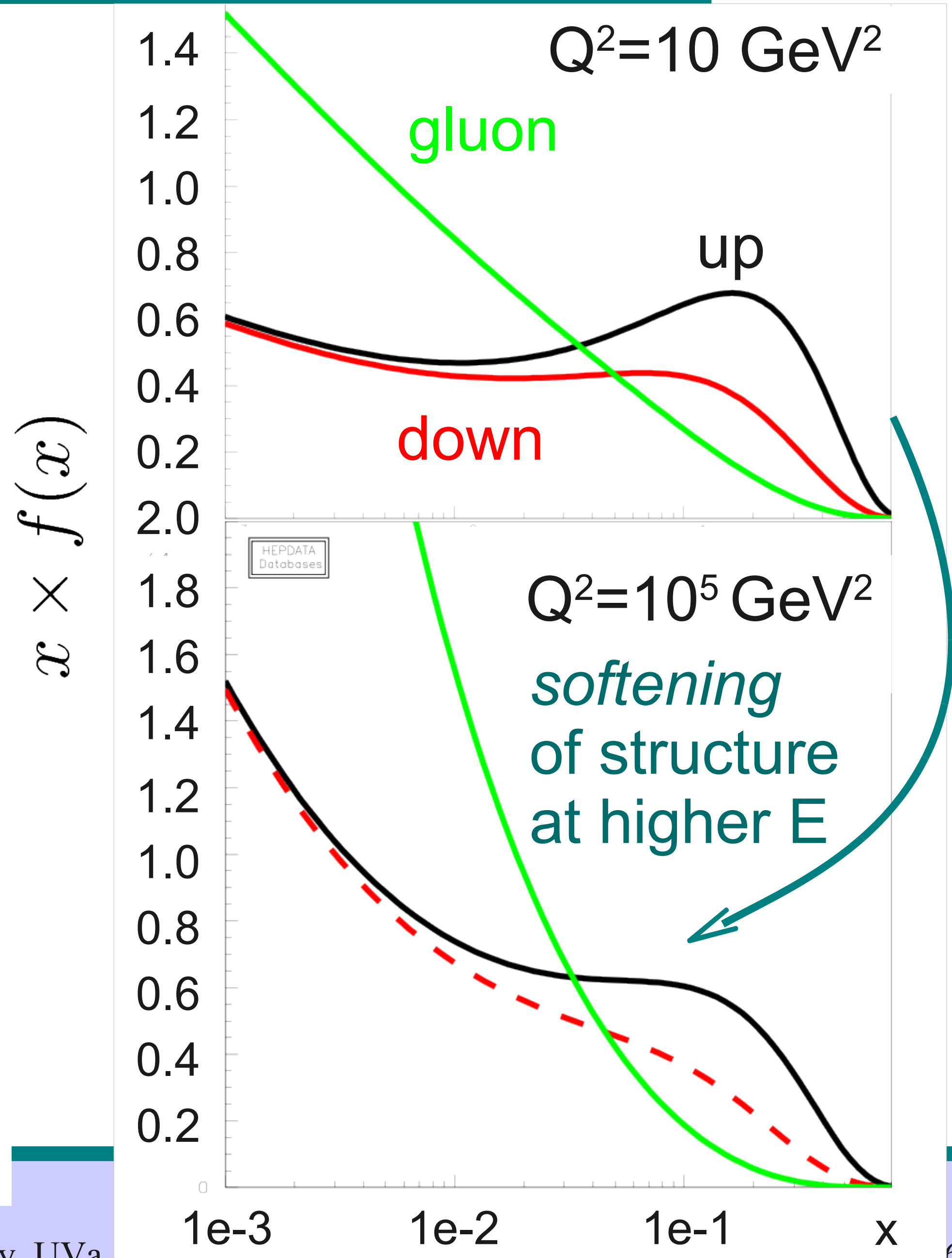
partial view of

Parton distributions in the proton

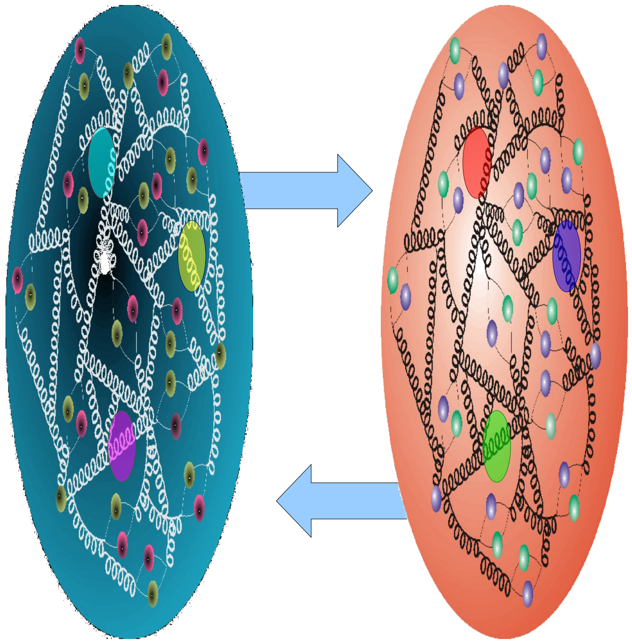
When colliding two protons, the parton soups interact.

Our initial state and therefore the effective center of mass energy √**ŝ** in any collision is a random process, determined by the probability to find a parton of type ***i*** with a fraction ***x*** of the momentum of the incoming proton.

High probability of finding low-x partons. Lot's of soft collisions for every hard scatter involving a large fraction of the proton's momentum => need MANY collisions to do **high energy** physics.



Seems messy...



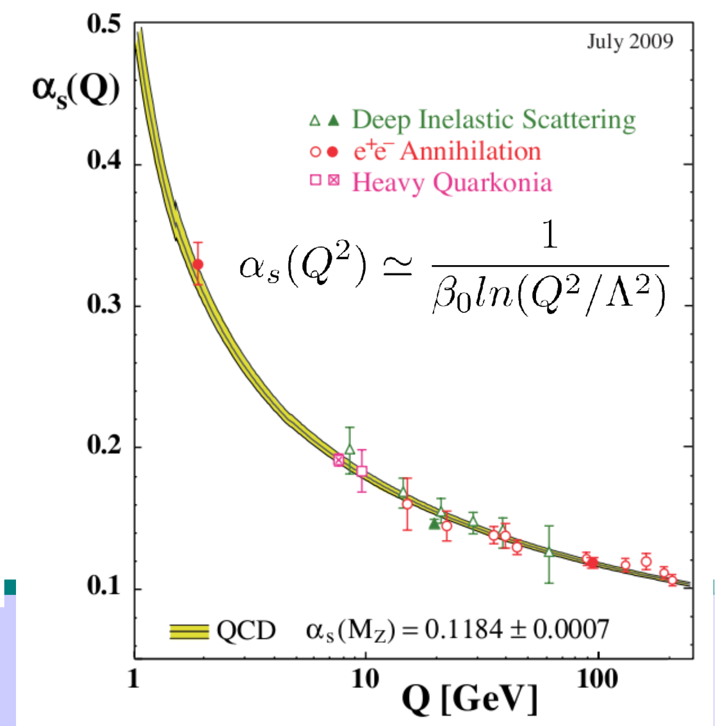
You don't use quantum mechanics to describe a bulldozer (or other macroscopic ensemble), why can we do it here?

We have many partons of varying momenta, all capable of interacting,why might we expect this to be sensibly describable?

Asymptotic freedom saves us. Strong coupling constant weakens at large Q^2.

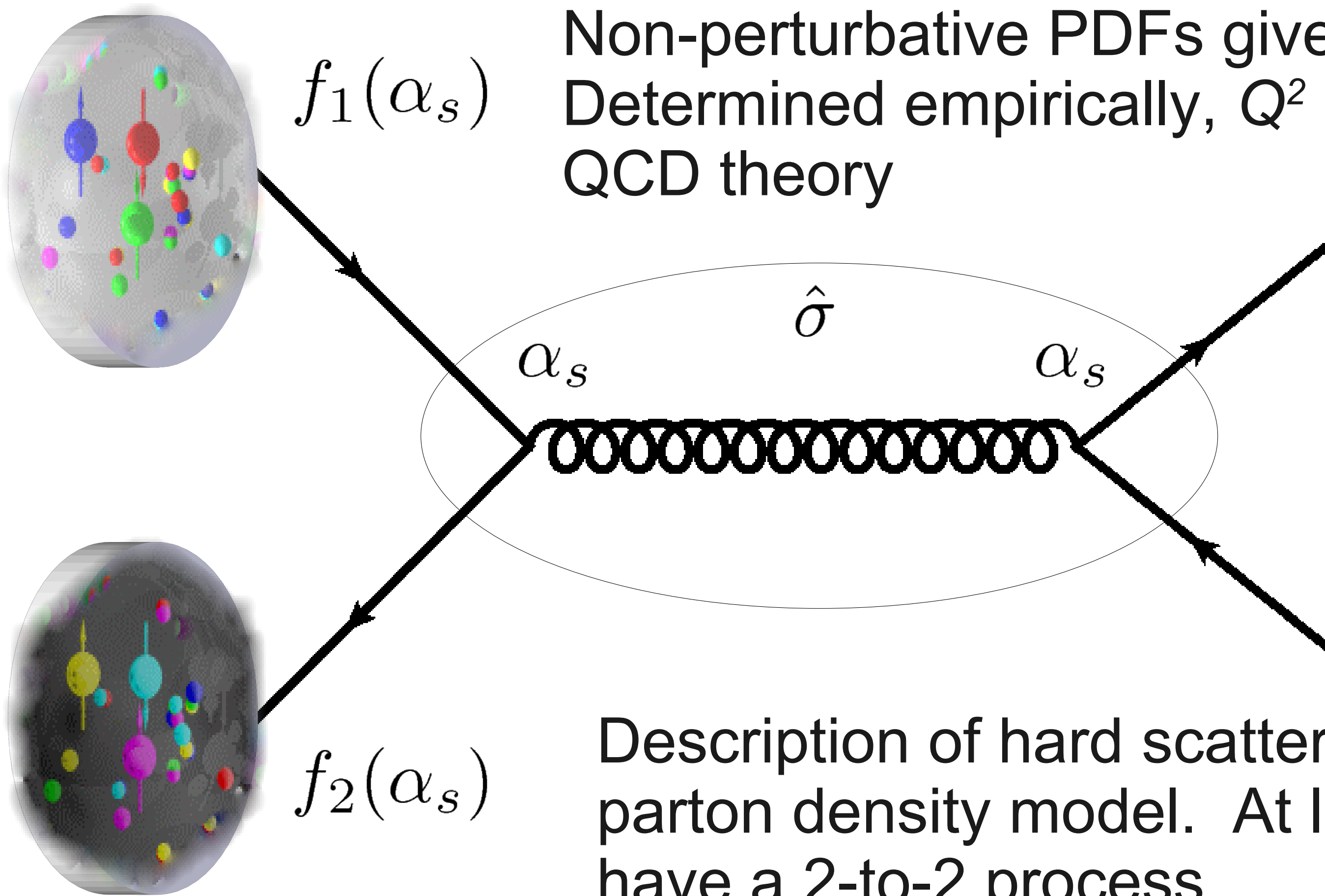
• Leads to confinment at large distance (low Q^2) scale $O(R_{proton})$

• But a hard interaction freezes out *spectators* and colliding partons act as if free



$P\bar{P}$ collisions and jet production

Non-perturbative PDFs give initial parton states. Determined empirically, Q^2 evolution according to QCD theory



Description of hard scattering factorizes from parton density model. At leading order (LO) we have a 2-to-2 process.

$P\bar{P}$ collisions and jet production

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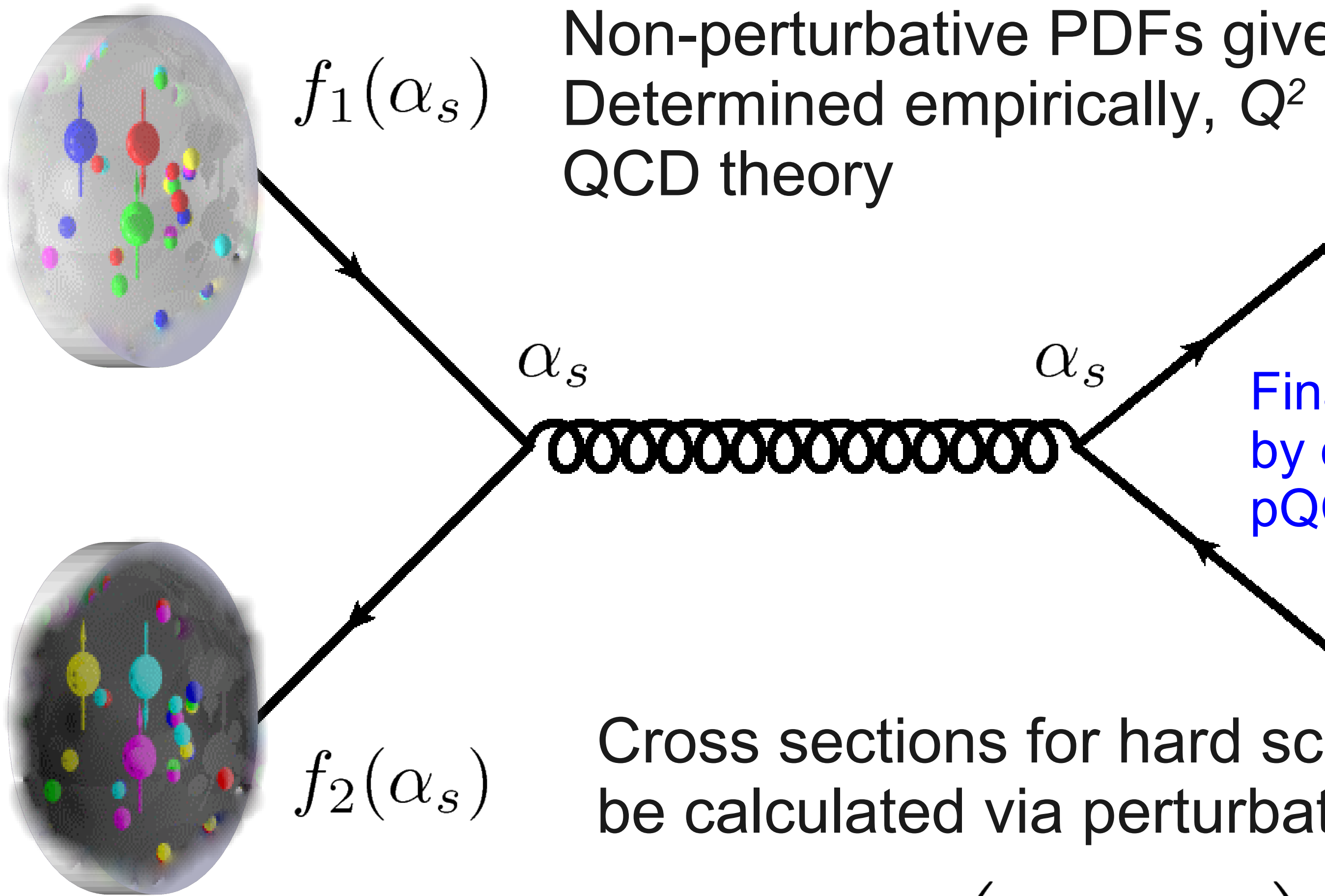
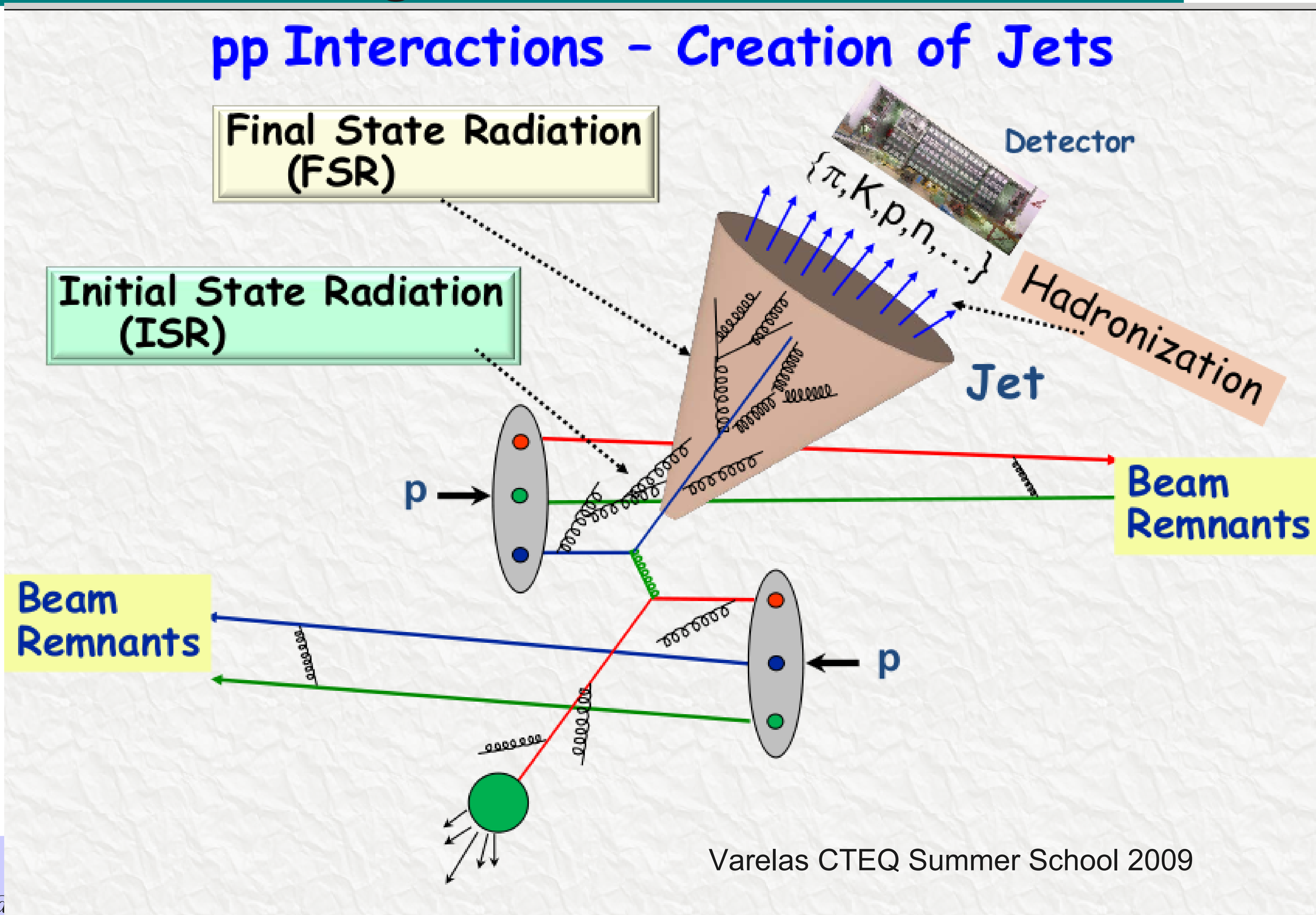


Final partonic states determined by convolution of PDFs and pQCD scattering amplitudes

Cross sections for hard scattering of partons may be calculated via perturbative expansion in QCD

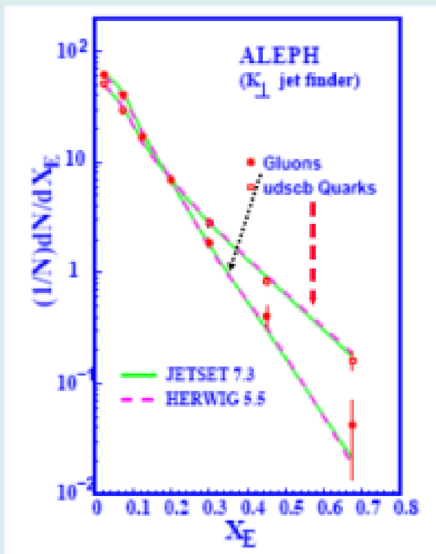
$$\sigma^{pert}(\alpha_s) = \left(\sum_n \alpha_s^n c_n\right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

Moving into the final state

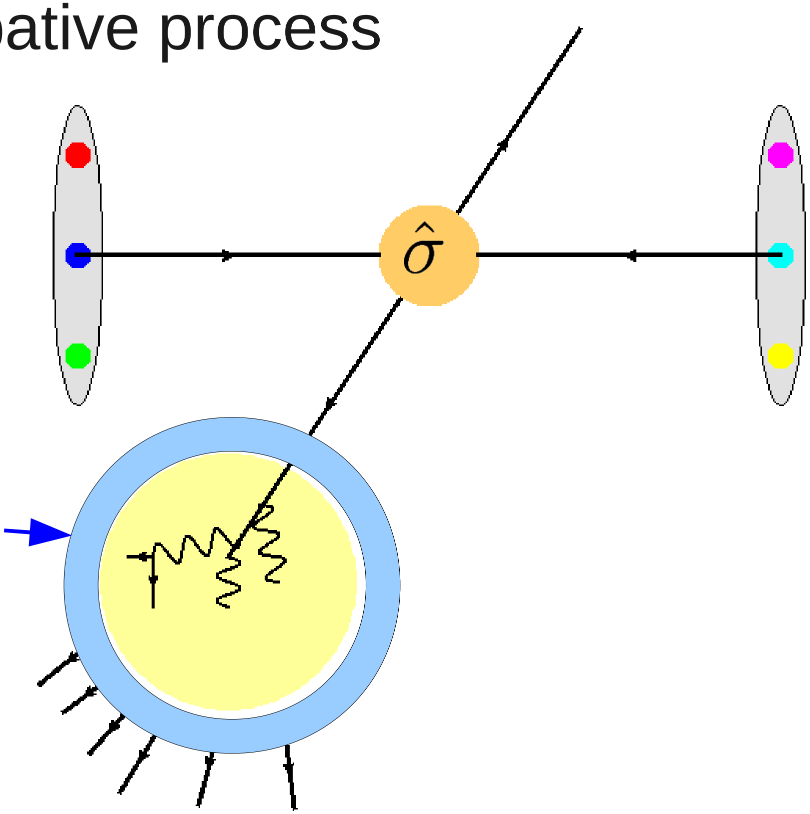


Fragmentation

Particle Fragmentation Functions



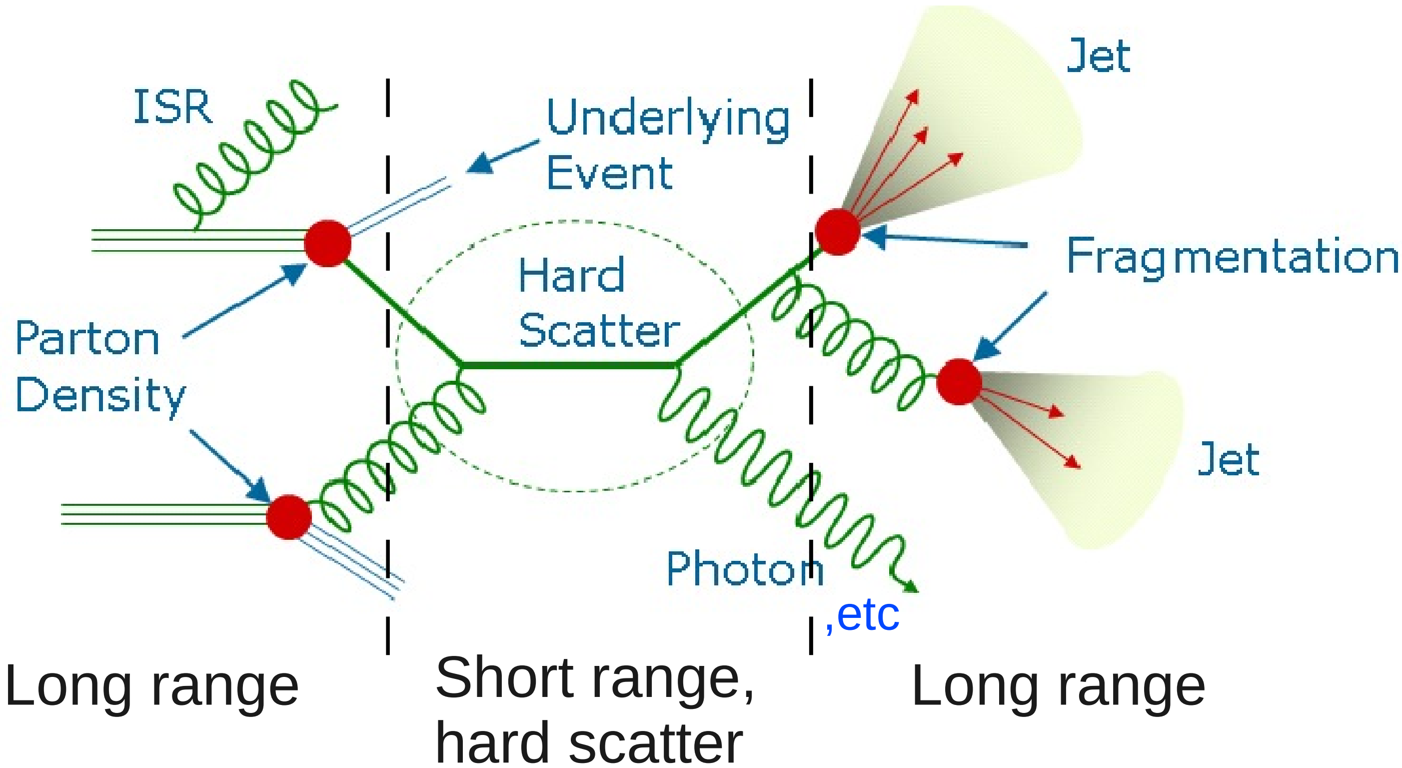
Outgoing parton fragments, another long-range, non-perturbative process



Fragmentation functions $D_{h/d}(Z_h,\mu_F)$ model the probability of finding a particle of type h with a momentum fraction Z_h of the parent parton d

- Determined from global fits of data from DIS and e+e-
- Quarks and gluons fragment differently
- “evolution” of the fragmentation functions can be calculated by pQCD

The long and the short of it



Problem “neatly” factorizes into a perturbative hard scatter (+ hard radiation),
Non-perturbative parton density and fragmentation models (+soft radiation).

Studying $p\bar{p}$ collisions

Accelerator energy is only part of the picture, b/c energy is split over many constituents, $p\bar{p}$ collisions scan wide range of $\sqrt{\hat{s}}$, or $E_{C.O.M.}$ in partonic reference frame.

Most interesting collisions are usually selected by identifying particles with high momentum transverse to the beam direction, high transverse momentum or p_T (often use transverse energy E_T synonymously)

Hard collisions (small impact parameter) can produce high p_T final states. Like Rutherford scattering...

This forms the basis of many jet triggers, fast ID to process data in real time.

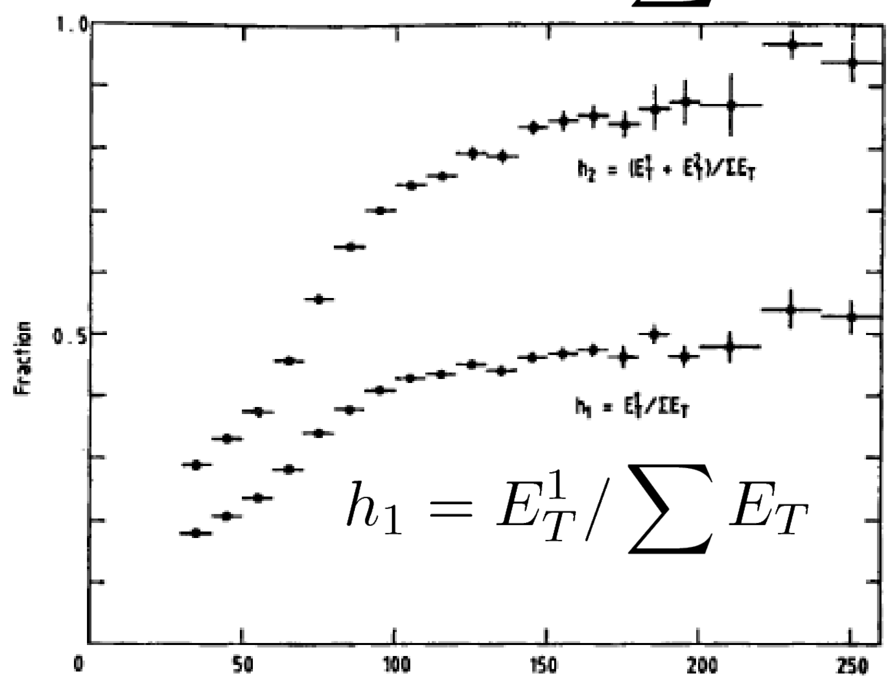
Note: a high momentum outgoing parton boosts fragmentation products into compact cone around the the original parton => jet!

UA2 1983, $p\bar{p}$ @ $\sqrt{s}$=540GeV

Jets in hadron collisions, early days

Define energy clusters as groups of adjacent calorimeter cells
Sum cells with E_T>0.4GeV

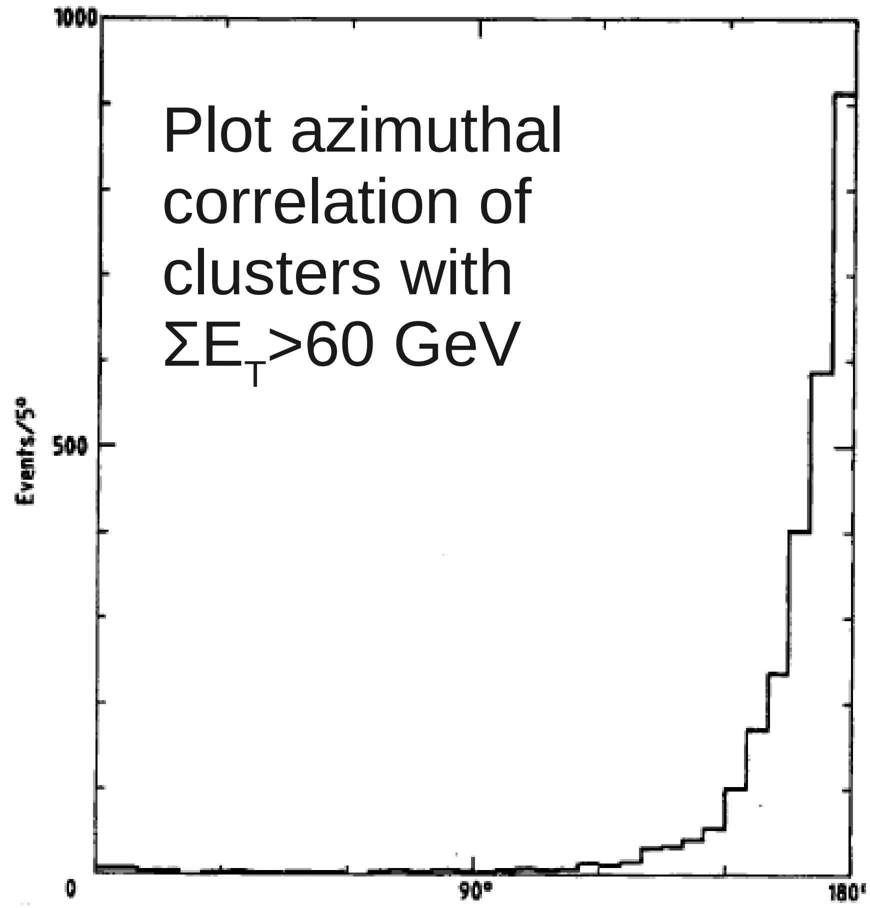
$$h_2 = (E_T^1 + E_T^2)/\sum E_T$$



$$h_1 = E_T^1/\sum E_T$$

$$\sum E_T$$

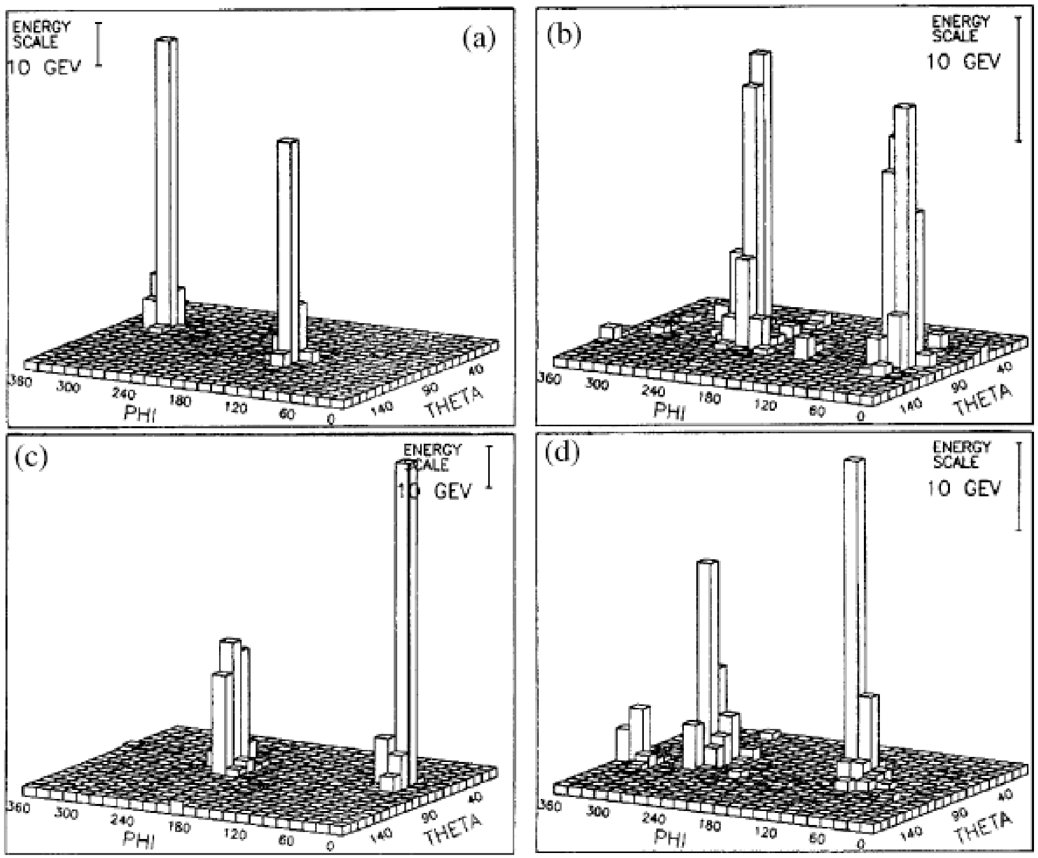
Plot azimuthal correlation of clusters with ΣE_T>60 GeV

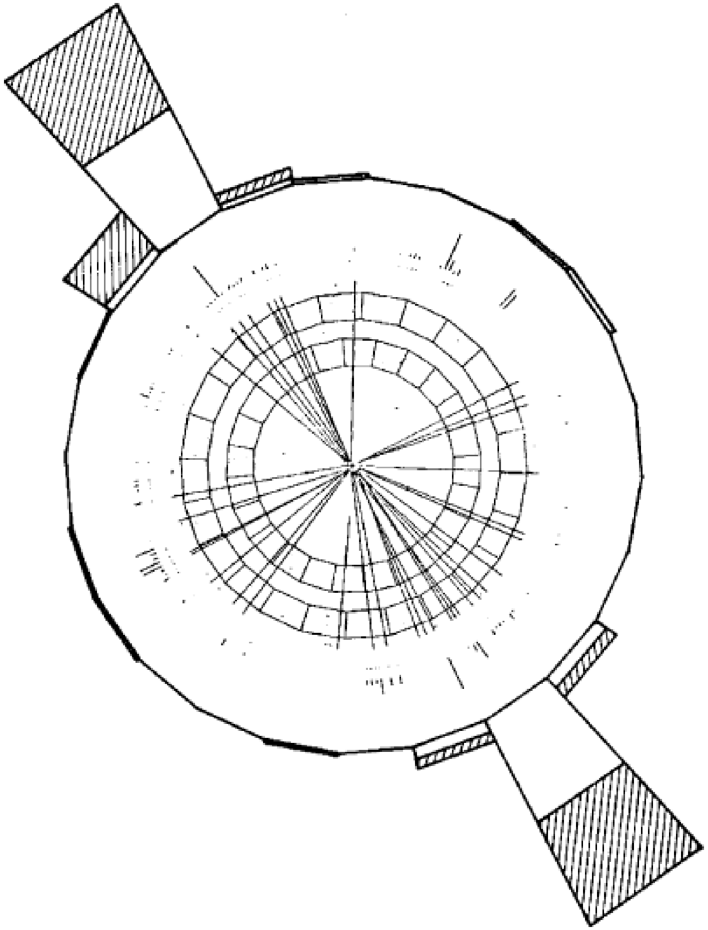


ΔΦ(cluster1,cluster2)

These are jets

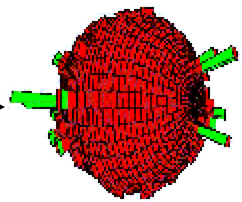
"typical events" with ΣE_T>100 GeV





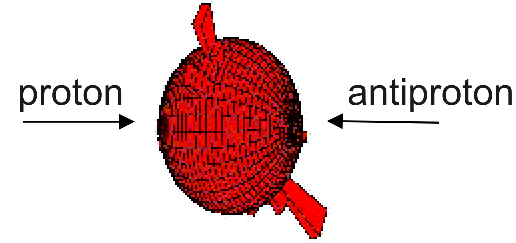
Effect of turning up the scale

Low E_T event

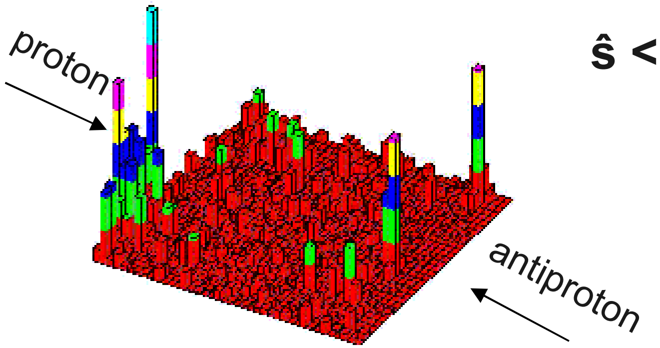


~an isotropic mess

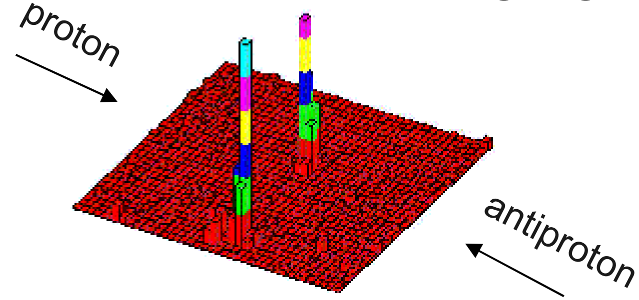
High E_T event



"Jets" balanced back to back

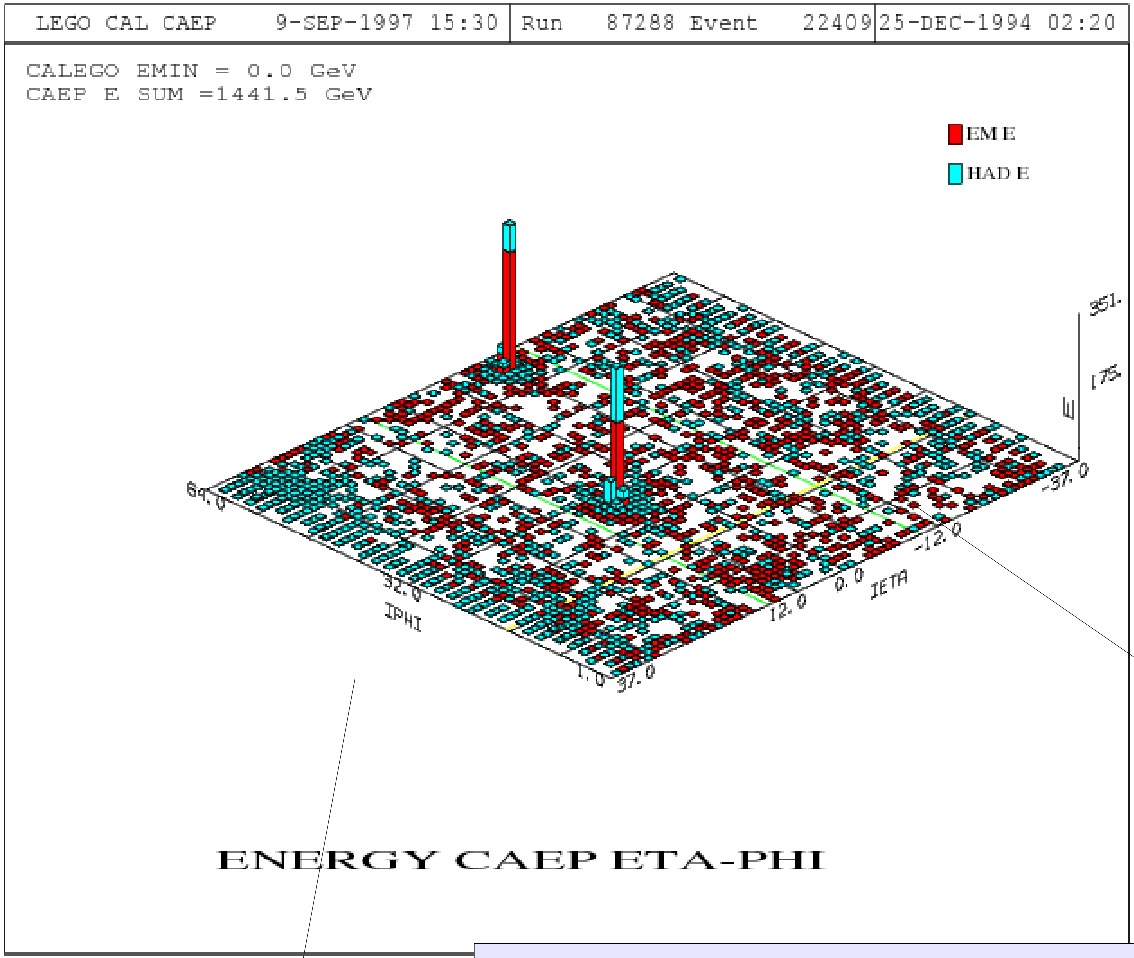


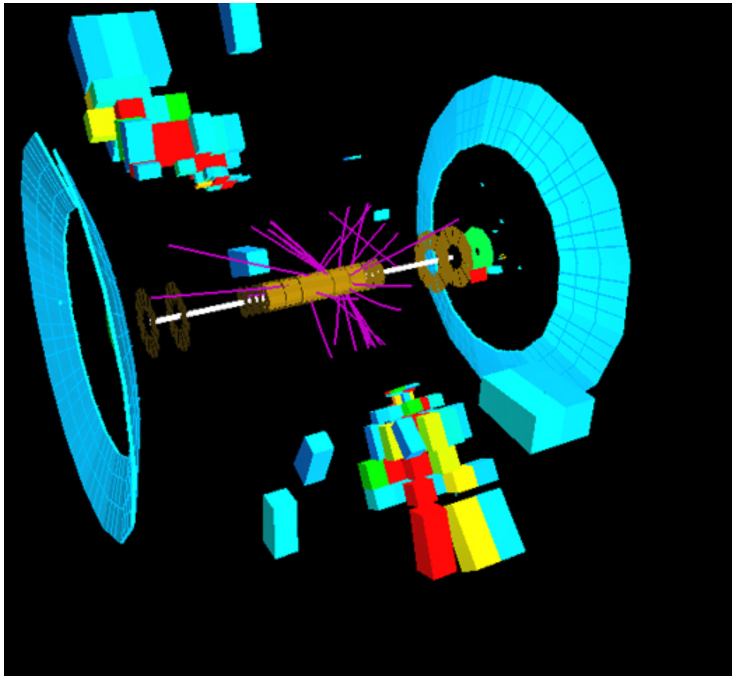
$\hat{s} << s$



$\hat{s} \sim s$

More jets





Another typical jet event

The two partons initiating these jets at DØ, carried about 2/3 of the incoming protons' momentum!

Notice
Low-level
“underlying event”

I know one when I see one...

But what is a jet?

Important point: A jet is what you define to be a jet.

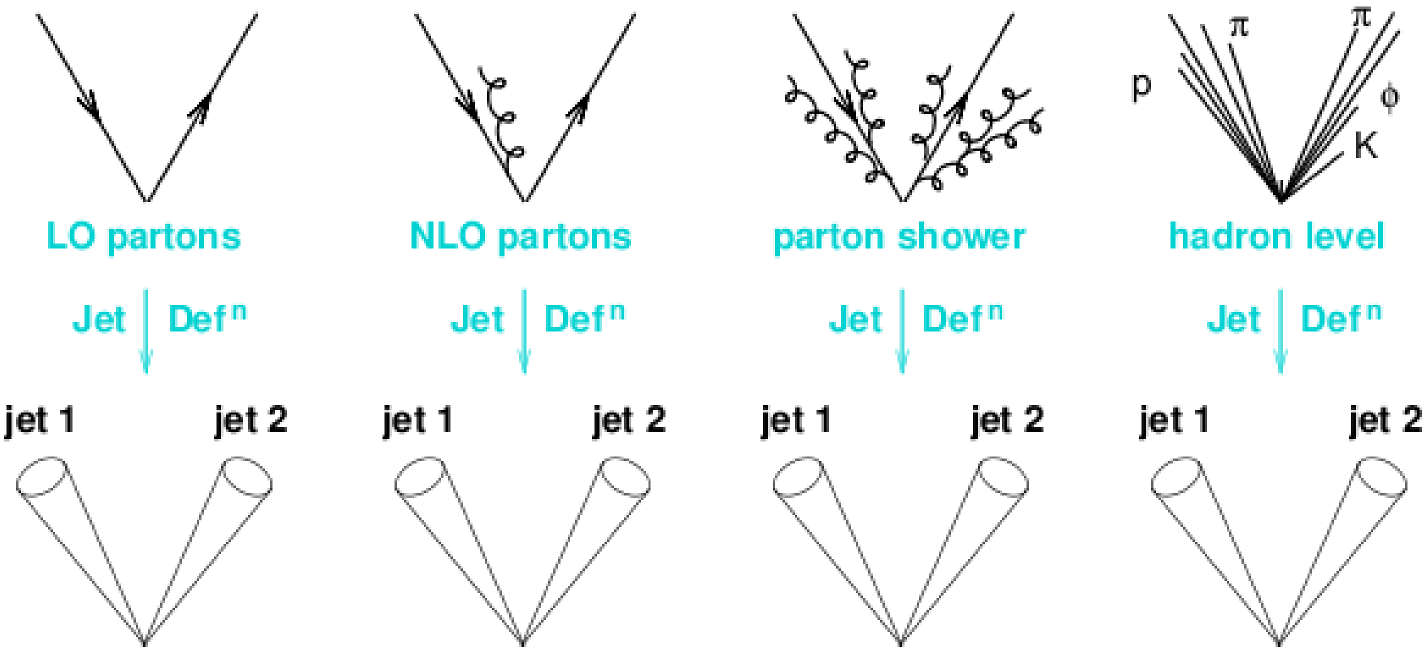
We're not dealing with elementary objects: (e, gamma, μ, etc).
Jets are defined by algorithms, different algorithms find different jets.

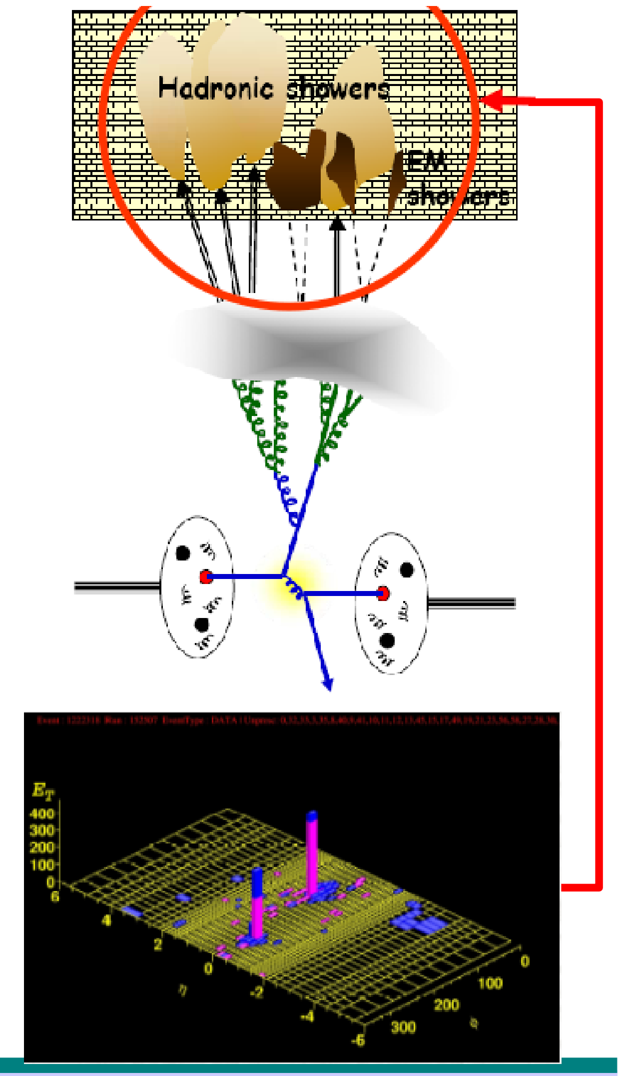
A good jet algorithm:

• Gives consistent results whether applied to partons, particles after hadronization, or to detector-level information (tracks, energy clusters, ...)
• Is relatively stable wrt. noise,overlapping energy from soft collisions, hadron remnants
• Is *relatively straightforward* to calibrate (good resolution, smallish corrections, ...)

Jet algorithms

G. Salam

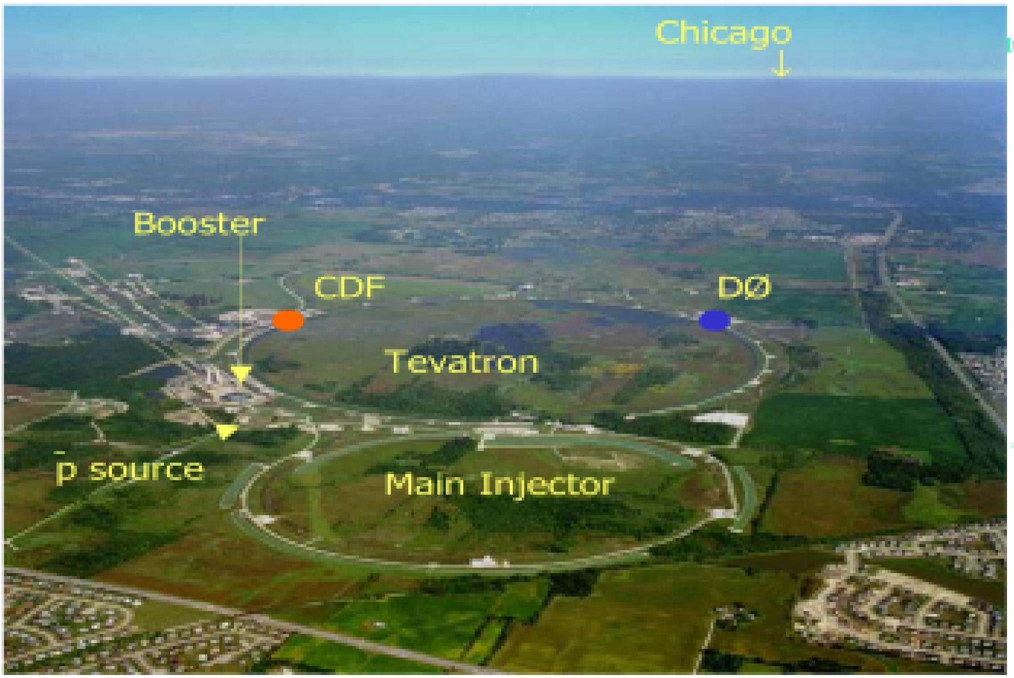


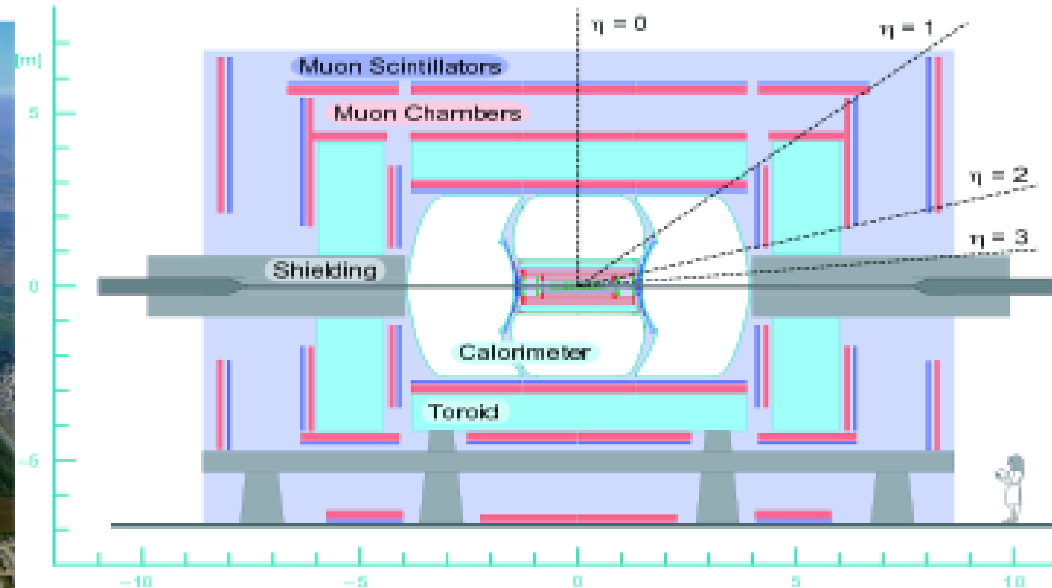


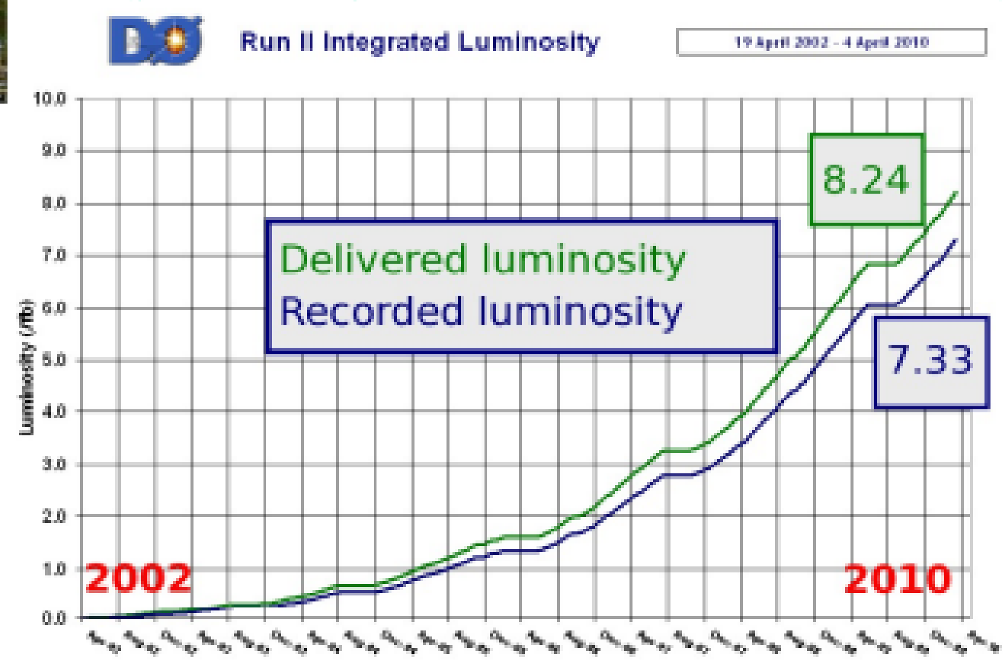
Projection to jets provides "universal" view of event

For a review of jet algorithms, see the excellent overview by Gavin Salam at
Previous LHC@BNL workshop:
https://indico.bnl.gov/conferenceDisplay.py?confId=206

The Tevatron and DØ







- $\sqrt{s} = 1.96\text{TeV}$
- Peak luminosity $4.0 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1}$
- Integrated luminosity $> 7\text{fb}^{-1}$

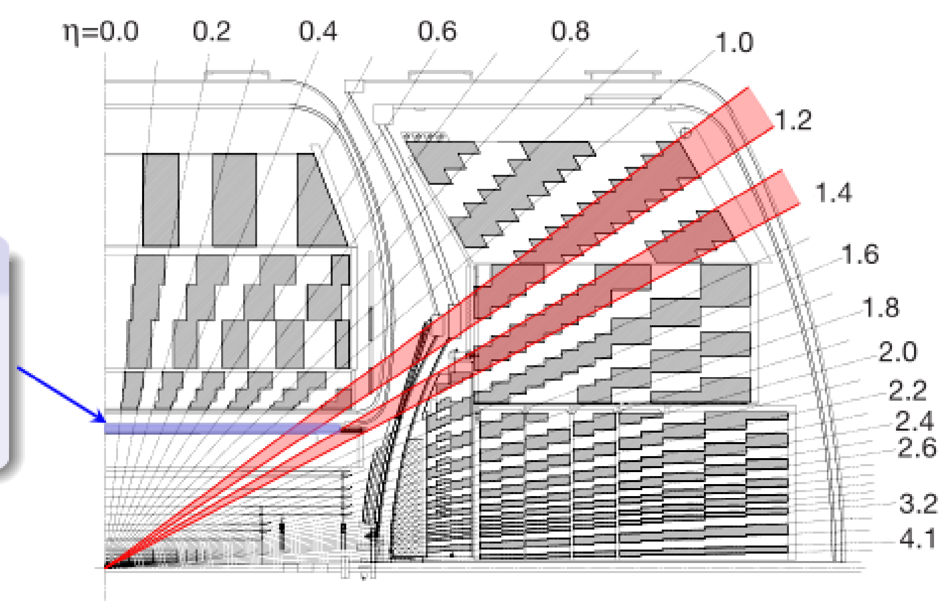
Measuring jets

Building a great accelerator and detector, then defining jets is a good start, but reaching good levels of precision in jet measurements is a whole new effort...

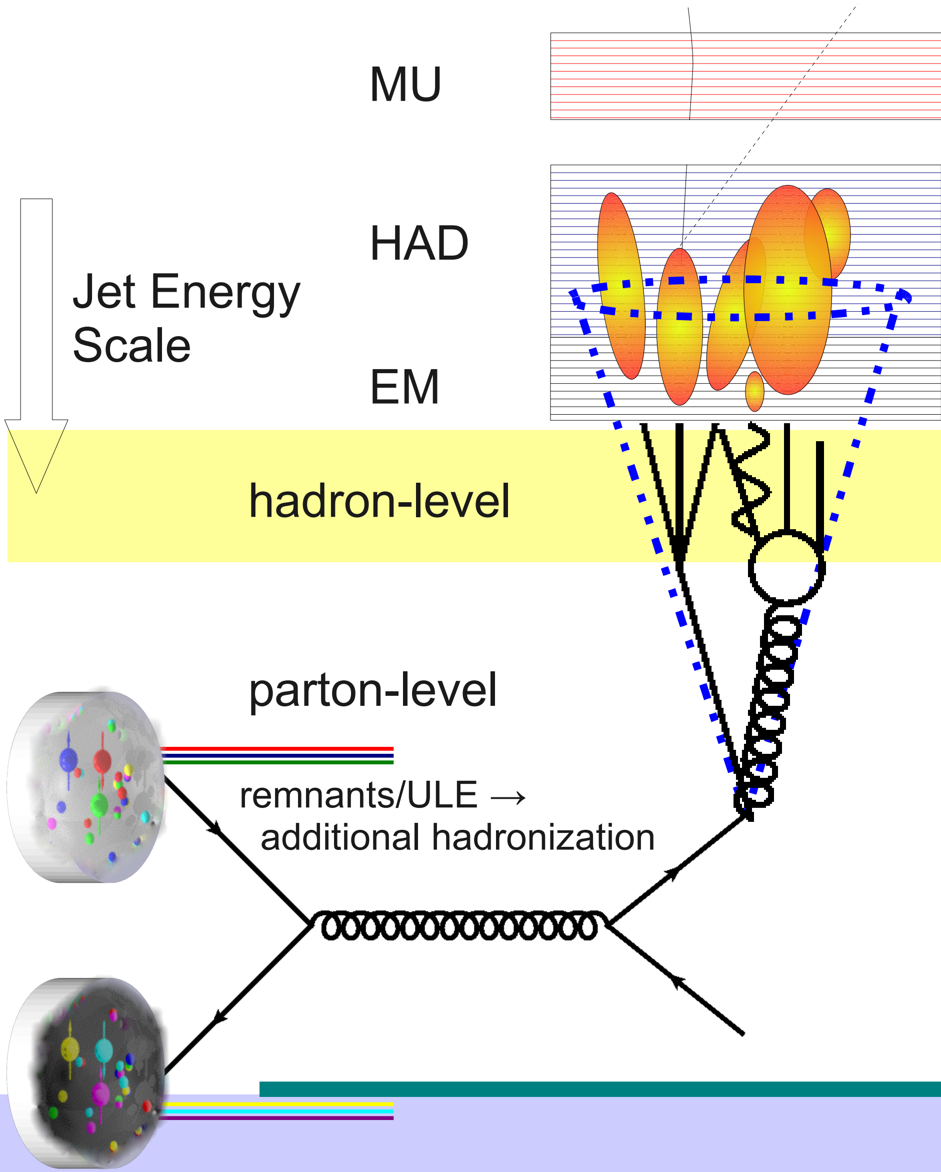
- Calorimeter cells make up pseudo-projective towers
- Four electromagnetic layers ($\approx 20\ X_0$)
- Three (central) or four (endcaps) finely segmented hadronic layers followed by one coarser hadronic layer. Hadronic depth > 7.2 (8.0) interaction lengths.
- Significant material in front of calorimeter: $\approx 4\ X_0$ (solenoid, preshowers, trackers)

Preshower detector

- Scintillating fibers
- Used to improve photon identification



Canonical picture of jet observables

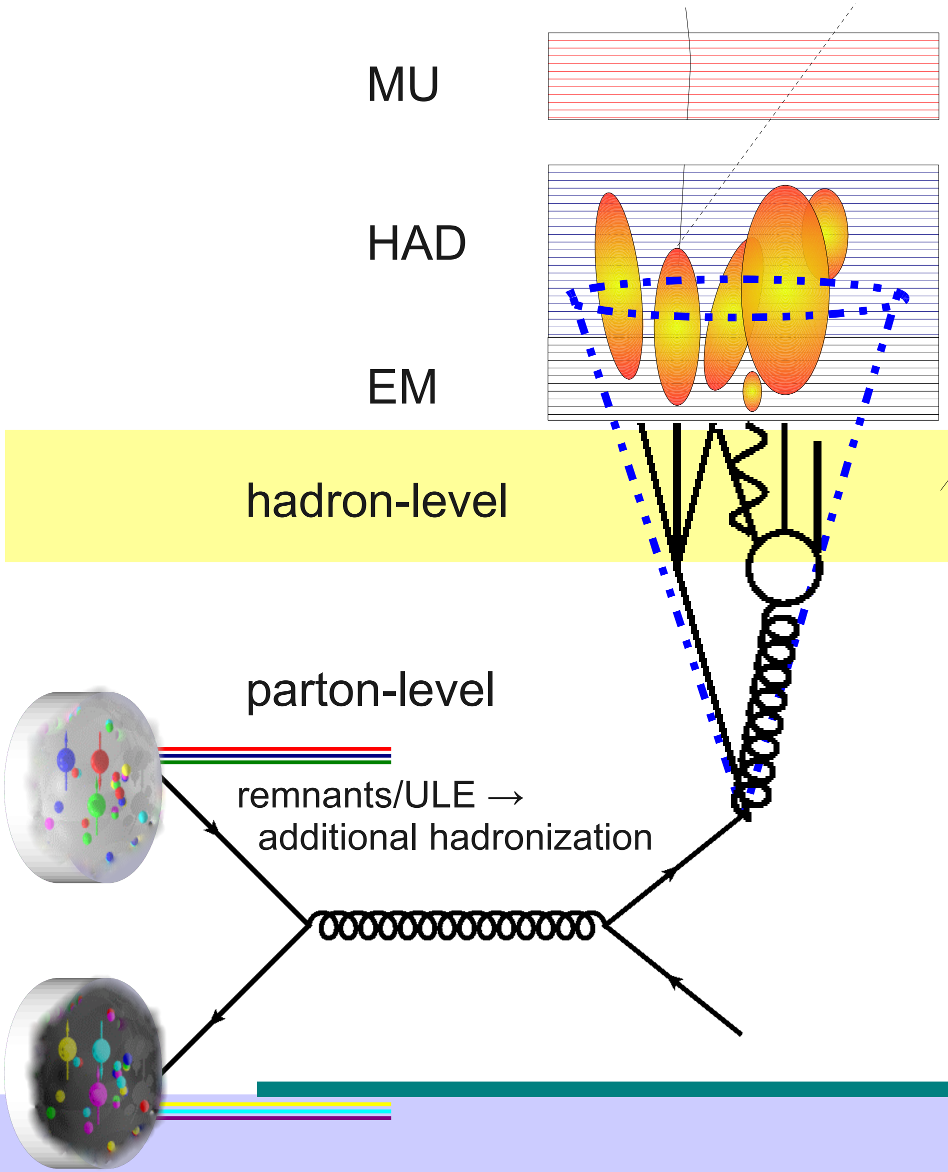


Clustering algorithm chosen to accurately define jets at detector particle, parton levels

Observed energies corrected to particle(hadron)-level expectations

pQCD calculations are corrected for non-perturbative effects of hadronization and underlying event

Canonical picture of jet observables



Clustering algorithm chosen to accurately define jets at detector particle, parton levels

Compare data/MC here

Observed energies corrected to particle(hadron)-level expectations

PQCD calculations are corrected for non-perturbative effects of hadronization and underlying event

Theory/experiment typically compared at particle-level

Jet Energy Calibration

Goal of the jet energy scale calibration:

To correct the calorimeter jet energy back to the stable-particle jet level before interaction with the detector

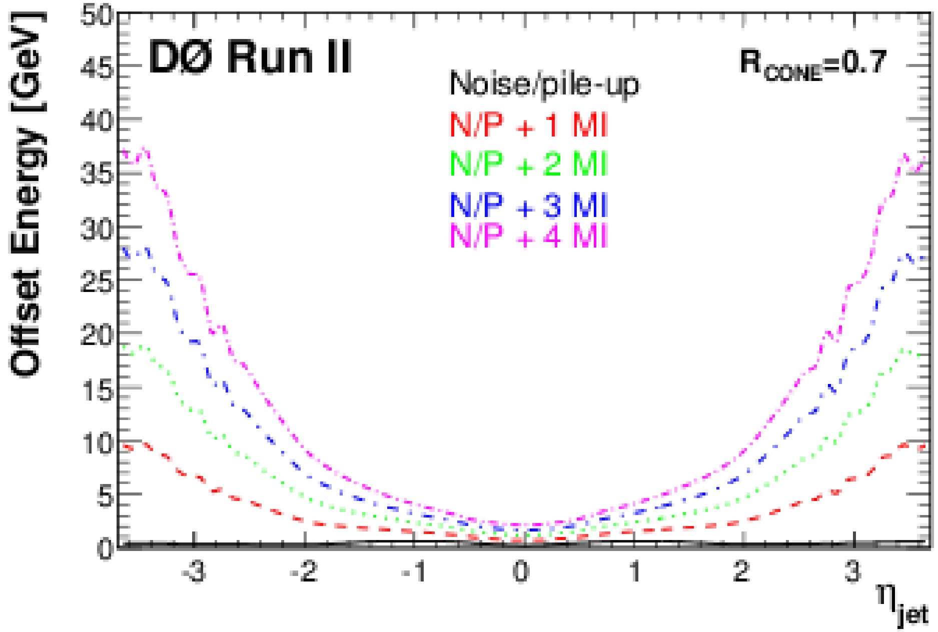
$$E_{\text{jet}}^{\text{ptcl}} = \frac{E_{\text{jet}}^{\text{meas}} - O}{F_\eta \cdot R \cdot S} \cdot k_{\text{bias}}$$

- O Offset subtraction removes all energy not associated with the hard scatter
- R Absolute calorimeter response
- F_η η-Dependent inter-calibration of response
- S Correction for detector showering effects

Offset Subtraction

Subtract all energy inside the jet cone not related to the hard interaction:

- electronics and uranium noise
- multiple $p\bar{p}$ interactions in the same bunch crossing
- left-overs from previous bunch crossings (pile-up)



Noise/pile-up

Estimated using zero-bias data; data triggered on the presence of bunch crossings and vetoing any hard interactions

Multiple interactions

Measured in minimum-bias data; data triggered using the luminosity monitors to signal potential inelastic scatters. Contribution from additional interactions determined from:

$$\mathrm{MI}(N_{PV}, L) = \mathrm{MinBias}(N_{PV}, L) - \mathrm{MinBias}(N_{PV} = 1, L)$$

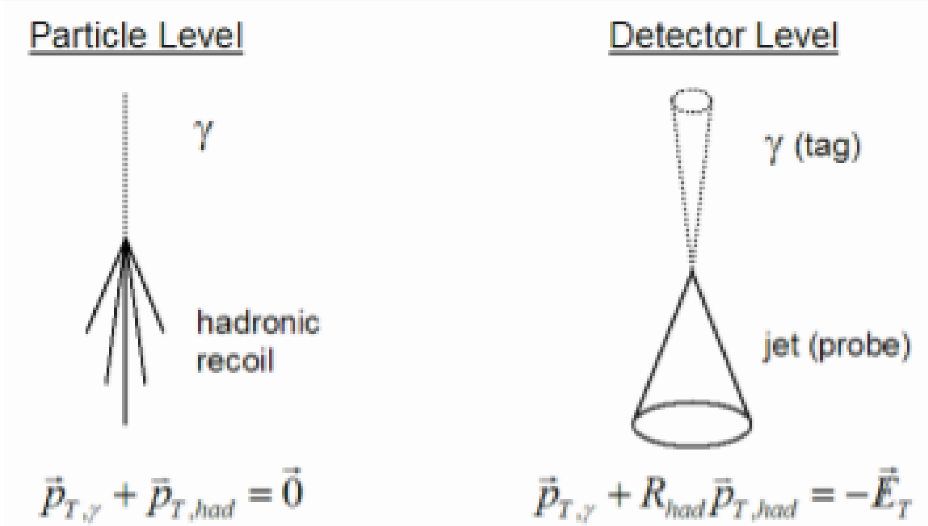
Absolute Response

Use a very tight photon+jet sample

- one photon within $|\eta| < 1.0$
- one jet within $|\eta| < 0.4$
- $\Delta\phi$(photon, jet) > 3.0

Missing transverse energy projection fraction method

- independent of the jet algorithm
- requires calibrated EM objects



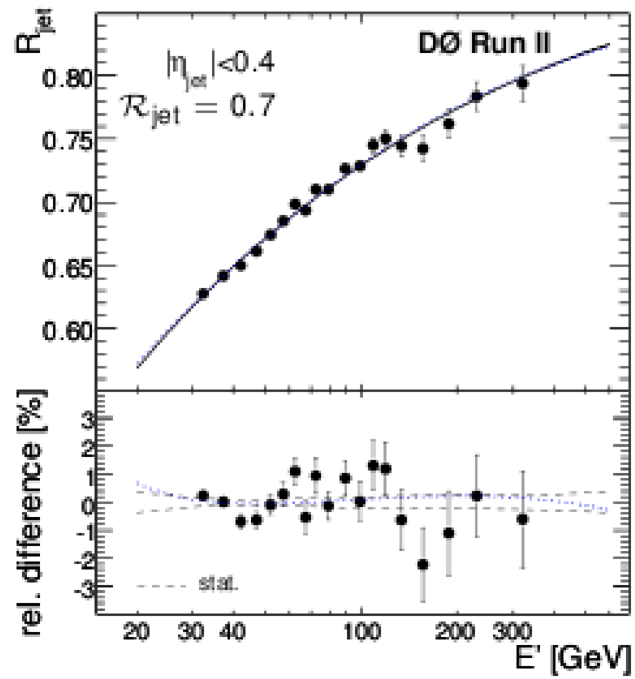
$$R_{\text{had}} = 1 + \frac{\vec{\not{E}}_{\text{T}} \cdot \vec{p}_{\text{T},\gamma}}{\vec{p}^{\,2}_{\text{T},\gamma}}$$

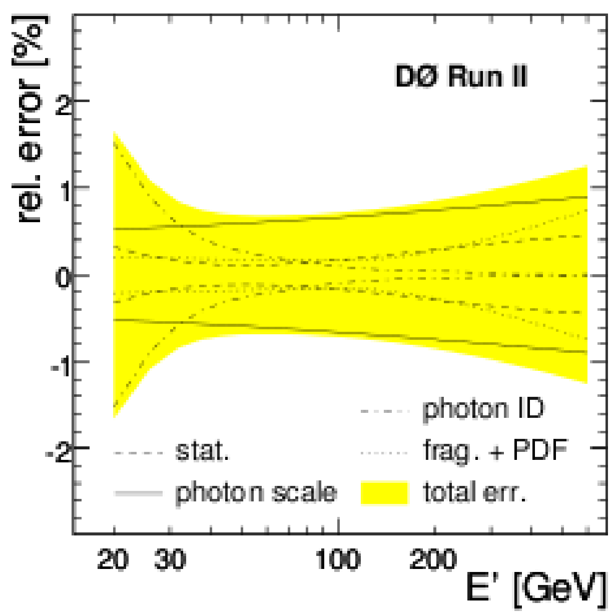
For tightly back-to-back objects:

$$R_{\text{jet}} \approx R_{\text{had}}$$

Absolute response

The $\approx 25\%$ correction to the response is the largest of all energy scale contributions



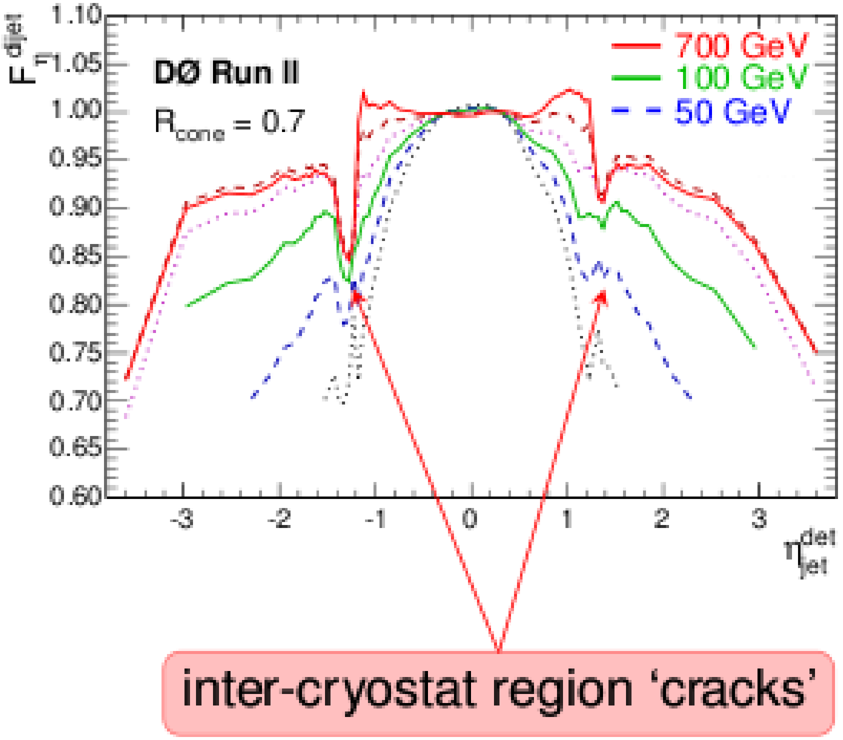


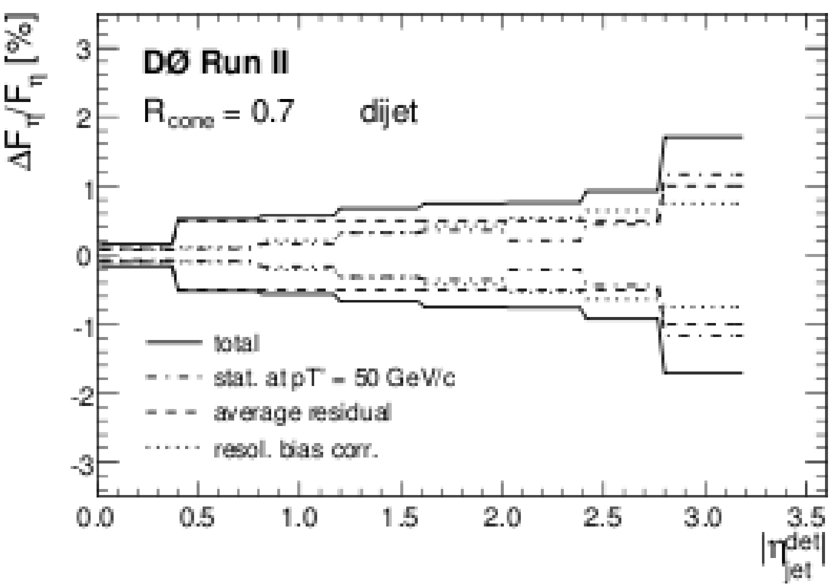
- Only $\approx 1.2\%$ uncertainty at $p_T = 600$ GeV/c
- The di-jet contamination in the photon+jet sample is measured in MC, verified in data and explicitly corrected for
- Parameterization vs. $E' \equiv p_{T,\gamma} \cosh \eta_{jet}$ suppresses effects of jet energy resolution

η-dependent corrections

Calibrate forward jets with respect to central ones

photon+jet	one tag photon within $\|\eta\| < 1.0$, contributes to low p_T region
di-jet	one tag jet within $\|\eta\| < 0.4$, contributes to high p_T region

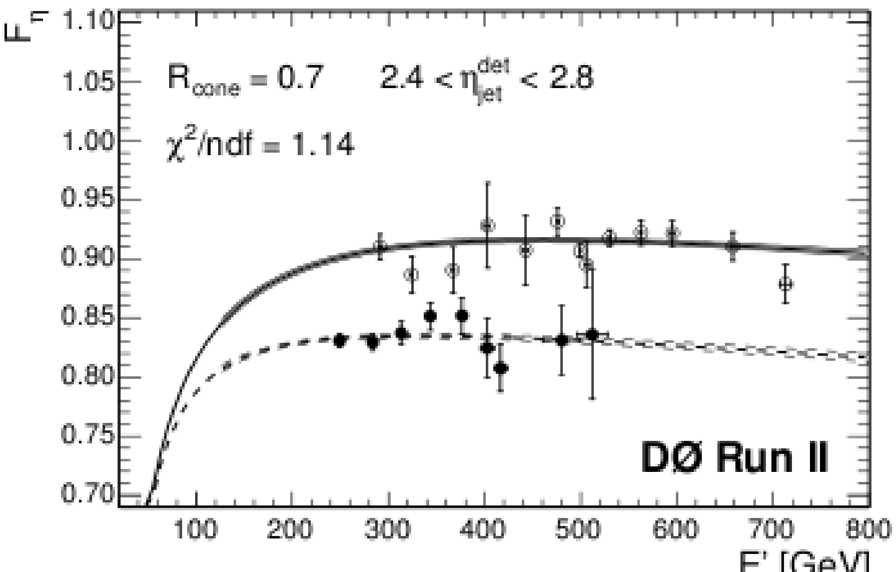




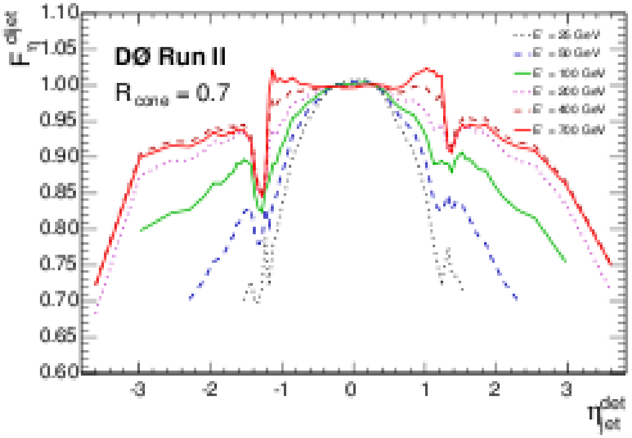
η-Dependent response corrections

Sample dependence

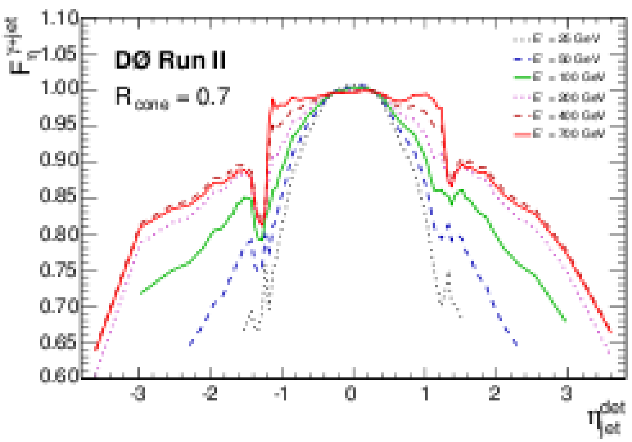
- Different response for gluon vs. quark jets
- Response difference increases going forward
- Relative quark/gluon contributions differ strongly between di-jet/photon+jet
- Di-jet sample used to extract shape of p_T dependence



di-jet



photon+jet



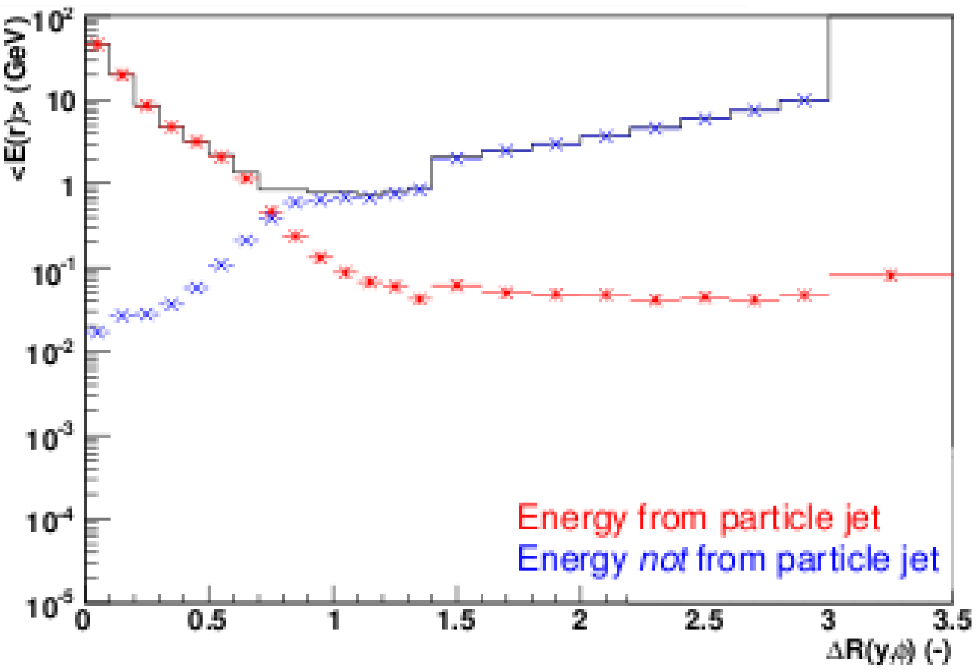
Detector Showering

Correct for instrumental showering effects: magnetic field bending, shower development in the calorimeter, . . .

- Use back-to-back photon+jet events and remove offset
- Map average energy deposited by jet particles vs. radial distance away from the jet
- Fitting the jet/not-jet energy templates to the data allows measurement of

$$S = \frac{\int_0^\infty E(\text{jet})}{\int_0^{\mathcal{R}_{\text{jet}}} (E(\text{jet}) + E(\text{not-jet}))}$$

$\mathcal{R}_{\text{jet}} = 0.7$, $|\eta_d| < 0.4$, $100 < p_T' < 130$ GeV/c



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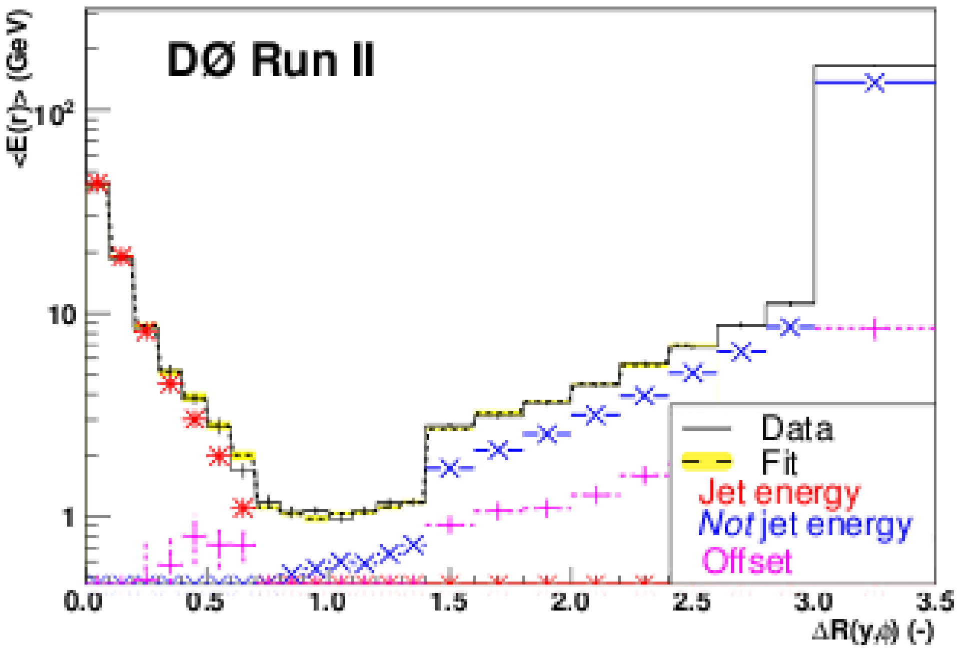
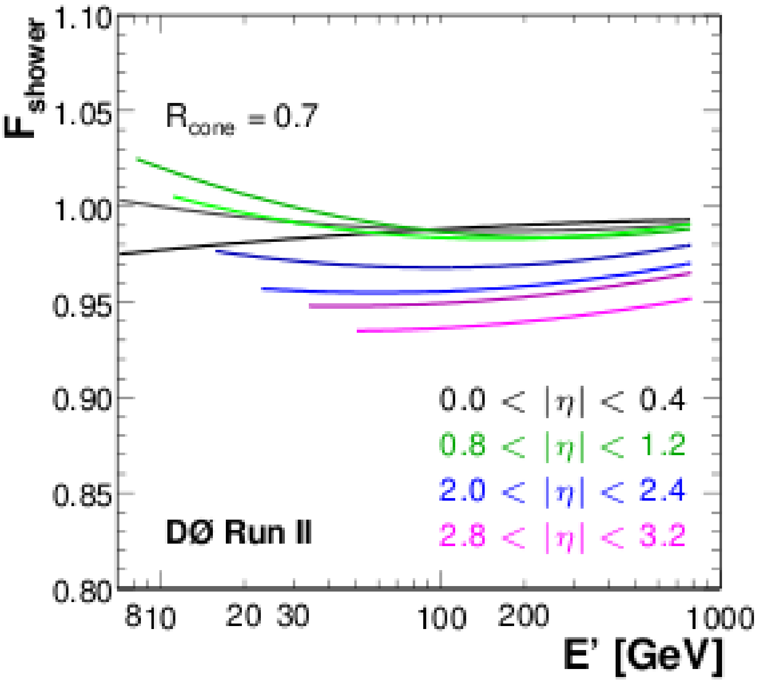
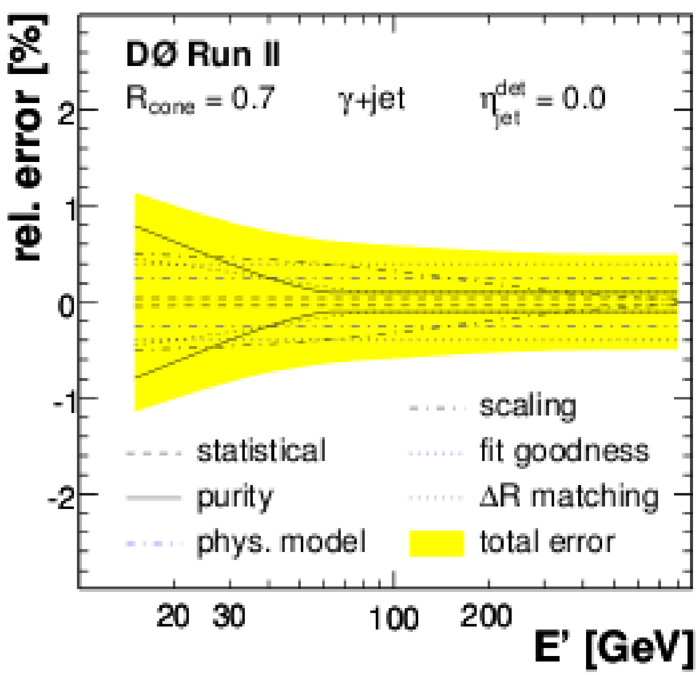


Detector Showering





- Calibrated using true showering in Monte Carlo
- Very small corrections compared to offset and response
- More prominent for smaller jet cone sizes
- Larger corrections for forward jets

- Main systematic uncertainties:
  - quality of the fit
  - photon purity (at low p_T)
  - jet fragmentation model (at high p_T)

Additional biases

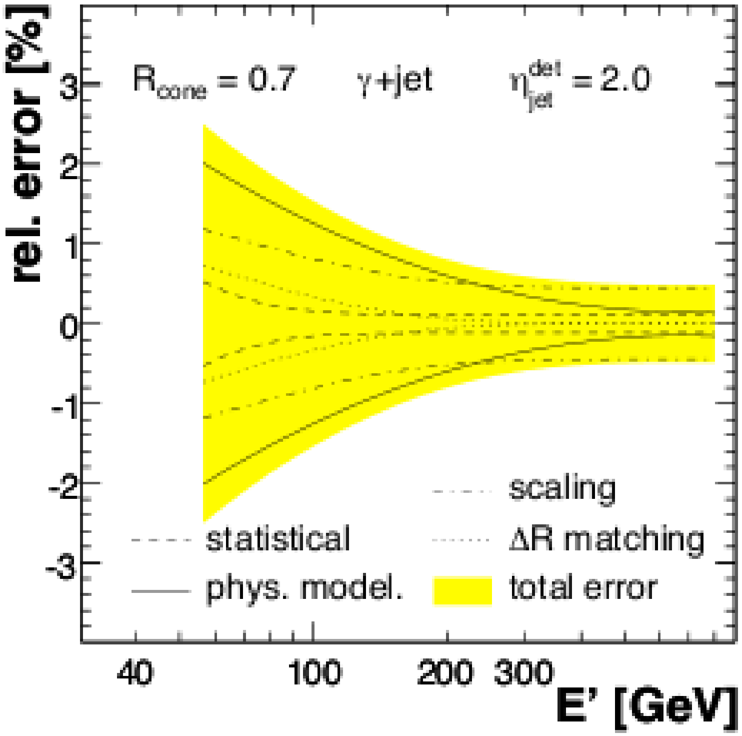
Side-effects of zero-suppression:

- The offset energy inside a jet is larger than the offset energy estimated in the absence of jets
- The compactness of photons with respect to jets makes photons less sensitive to zero-suppression effects: the MPF method underestimates the jet response.

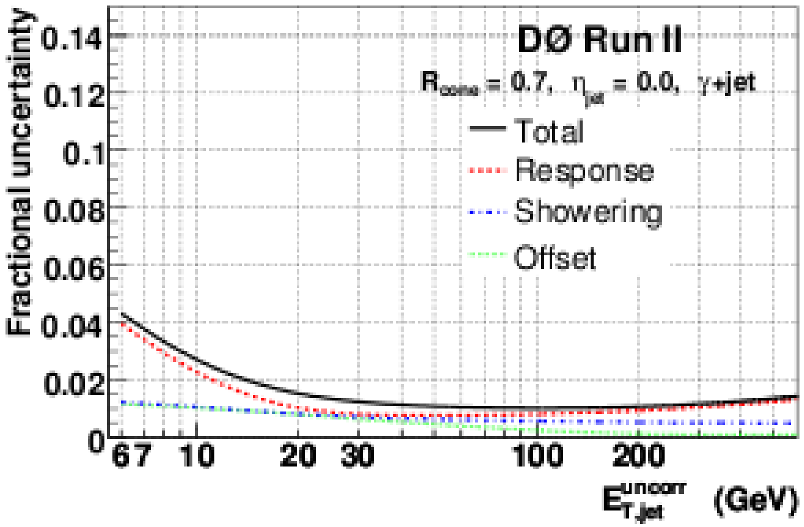
The above effects compensate to a large extent. The remaining effect is studied in MC by comparing offset and response for the same jets with and without ZB overlay.

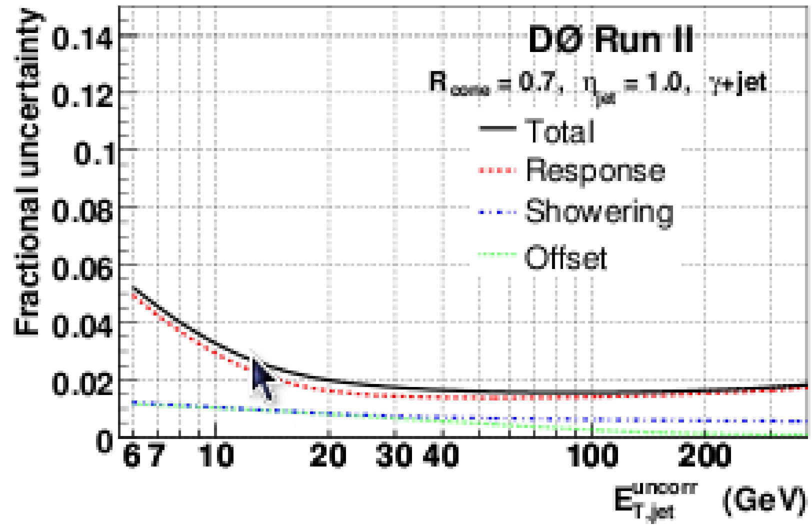
The MPF method is sensitive to additional activity in the event:

- jets below reconstruction threshold ($E_{T,\,min} = 6$ GeV)
- event selection, especially the minimum $\Delta\phi$(photon, jet) cut
- effects of jet splitting/merging
- underlying event

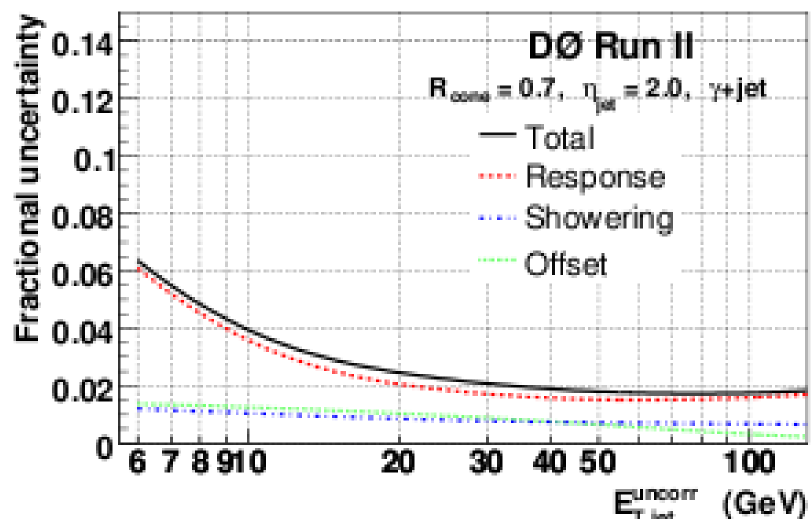


Combined JES corrections

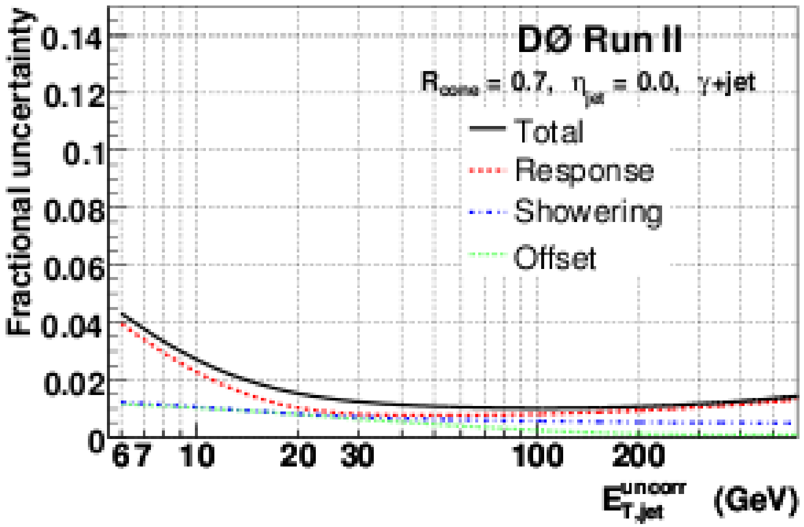


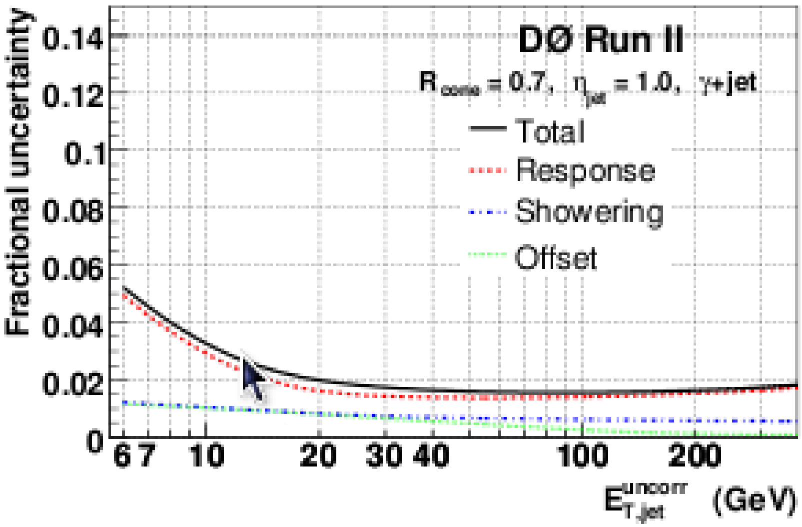


Fractional jet energy scale uncertainties for $\mathcal{R}_{\text{jet}} = 0.7$ cone jets at various $\eta = 0.0/1.0/2.0$ as a function of uncorrected jet p_T



Combined JES corrections





Dominant uncertainties:

- Absolute EM energy scale
- Electron-to-photon energy scale
- Photon purity in the photon+jet sample (esp. at low p_T and very forward)
- Low statistics at high p_T

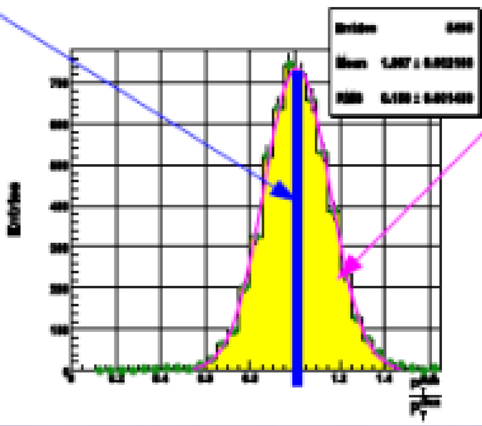
Most precise jet energy calibration ever achieved at a hadron collider

Several years of dedicated effort, and ongoing to maintain calibration withnew data.

Correcting jet measurements, resolution

Perfect detector:

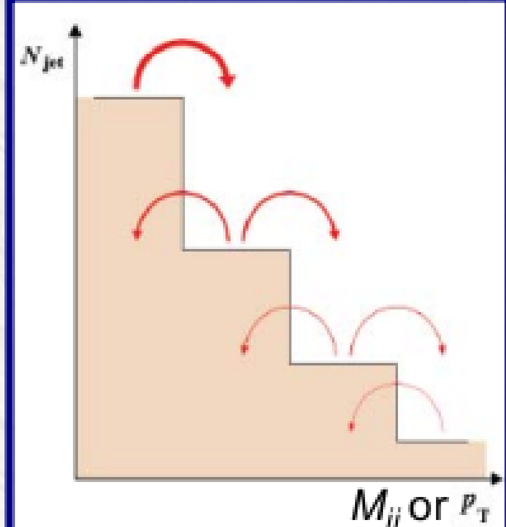
$$x = \frac{p_T^{observed}}{p_T^{particle}} = 1$$



Real detector:

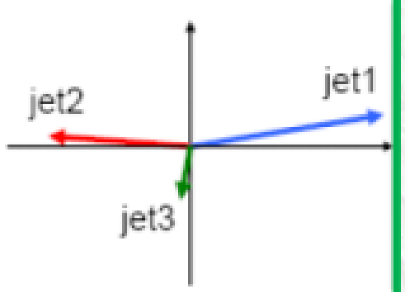
$$f = A e^{\frac{-(x-1)^2}{2\sigma^2}}$$

$$Resolution = \sigma(f)$$



- In true dijet events jets should balance exactly in p_T.
  In reality we usually see a small third jet contribution and a non-zero asymmetry in p_T given by:

$$A = \frac{(p_T^{jet1} - p_T^{jet2})}{(p_T^{jet1} + p_T^{jet2})}$$

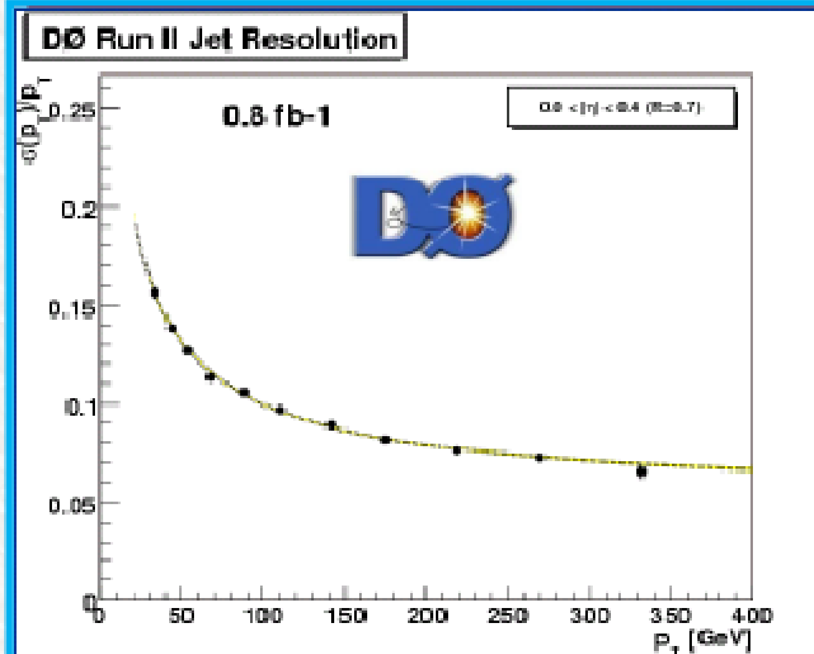


where jet1 and jet2 are

the 2 leading jets in the event

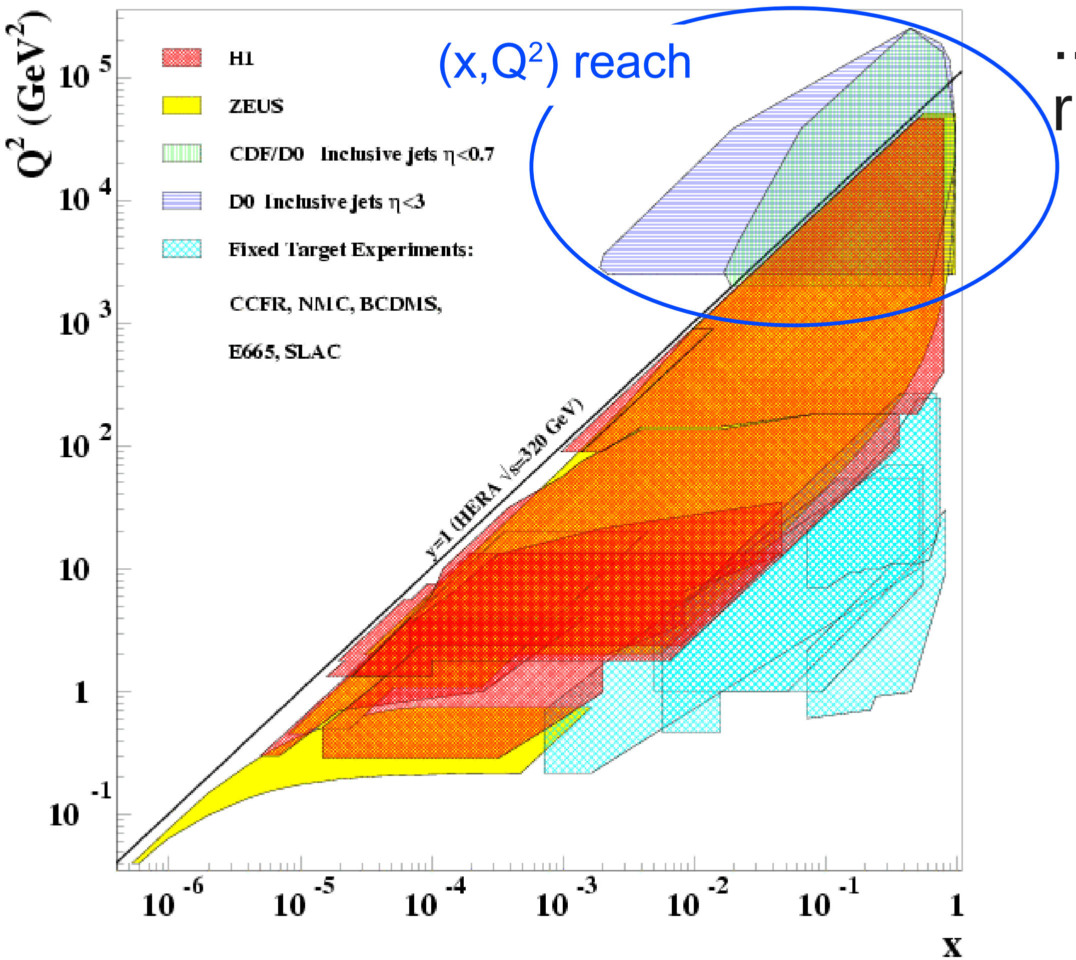
- The calorimeter resolution is related to the width of the asymmetry distribution by: $\frac{\sigma(p_T)}{p_T} = \sqrt{2}\,\sigma_A$

where σ_A is a sigma of the asymmetry distribution



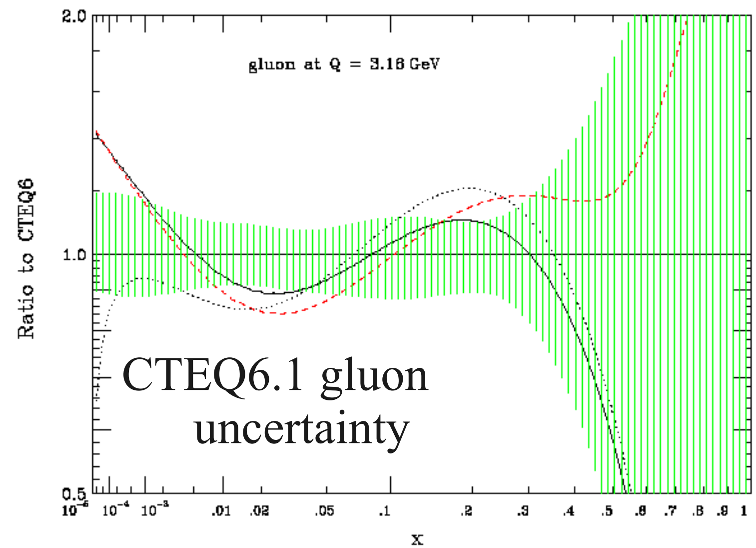
QCD with jets

Tevatron data provide unique and increasingly precise inputs with...



...large kinematic reach...

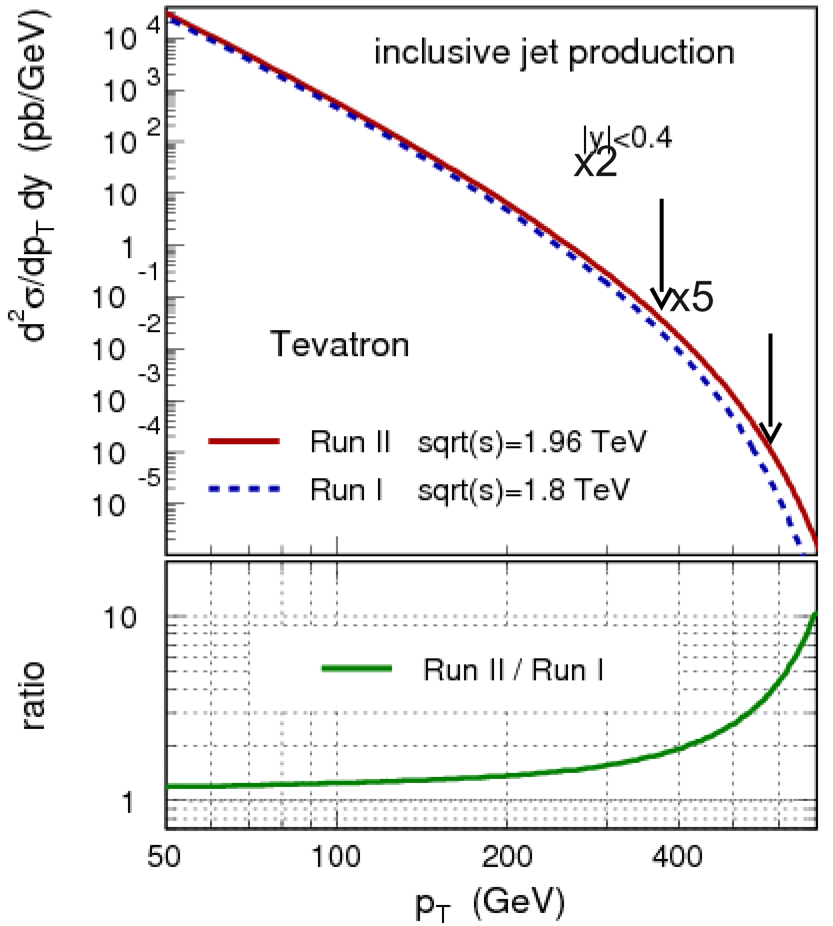
... into poorly constrained regions of pdf fits



Access to hardest partonic subprocesses, approach limit: $\sqrt{\hat{s}} \approx \sqrt{s}$

High P_T jets

Large high p_T cross section
→ unique sensitivity

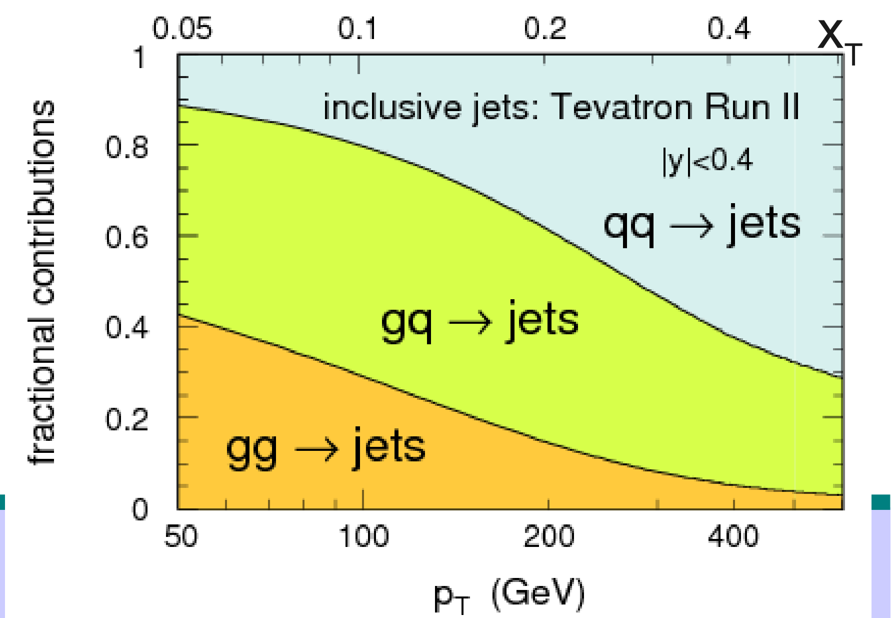


Run II: σ^{jet} increased x5 at p_T= 600GeV

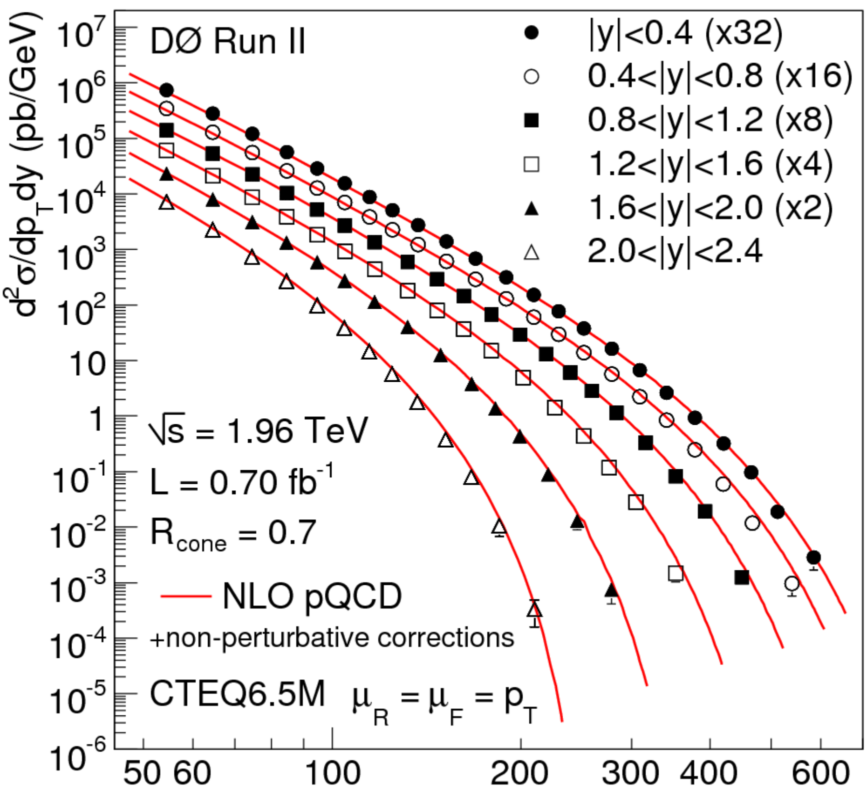
- sensitive to new physics:
  quark compositeness,
  extra dimensions, …(?)…

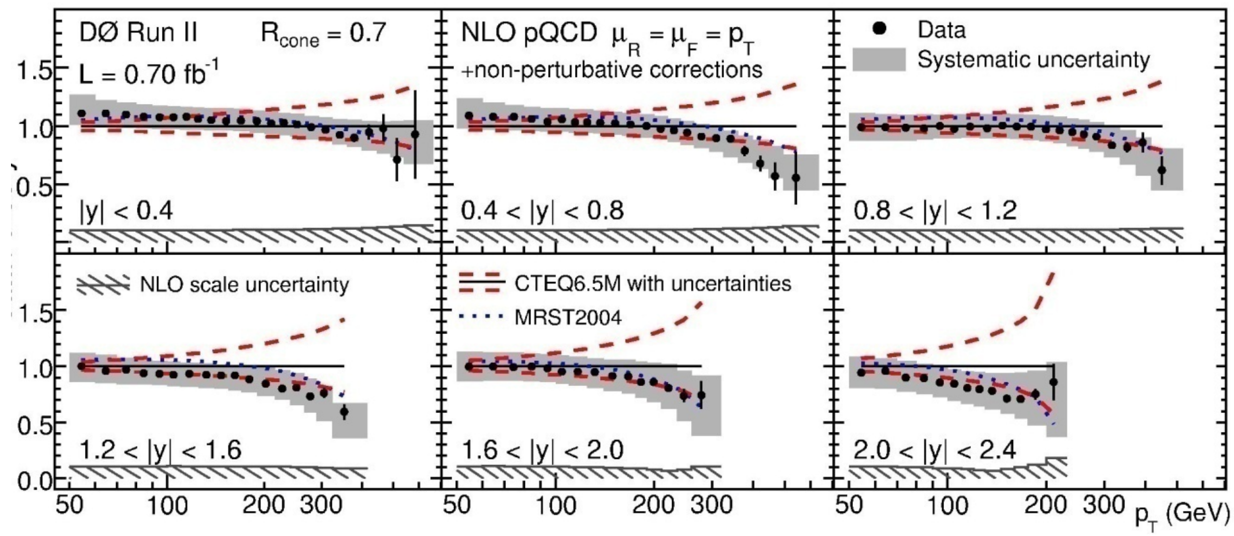
Theory @NLO is reliable (±10%)

- sensitivity to PDFs, dynamics, α_s
- unique reach for high-x gluon



Inclusive jet production





p_T (GeV)

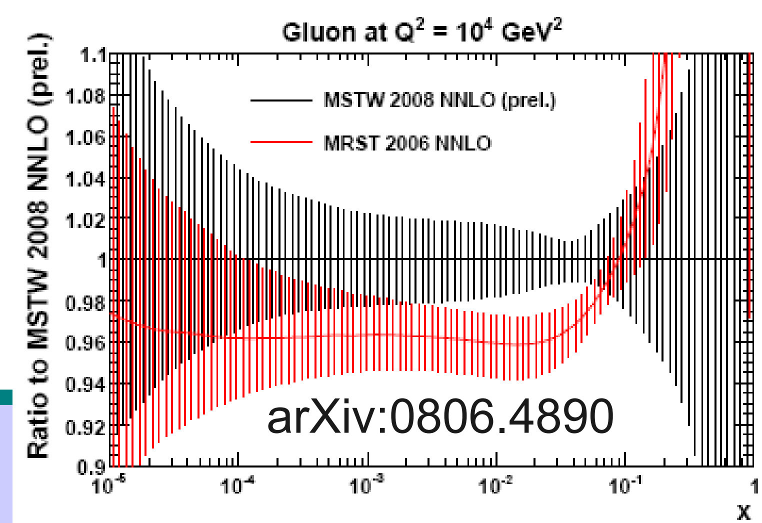
~9 decades measurement!

shape well described by pQCD/ MRST2004

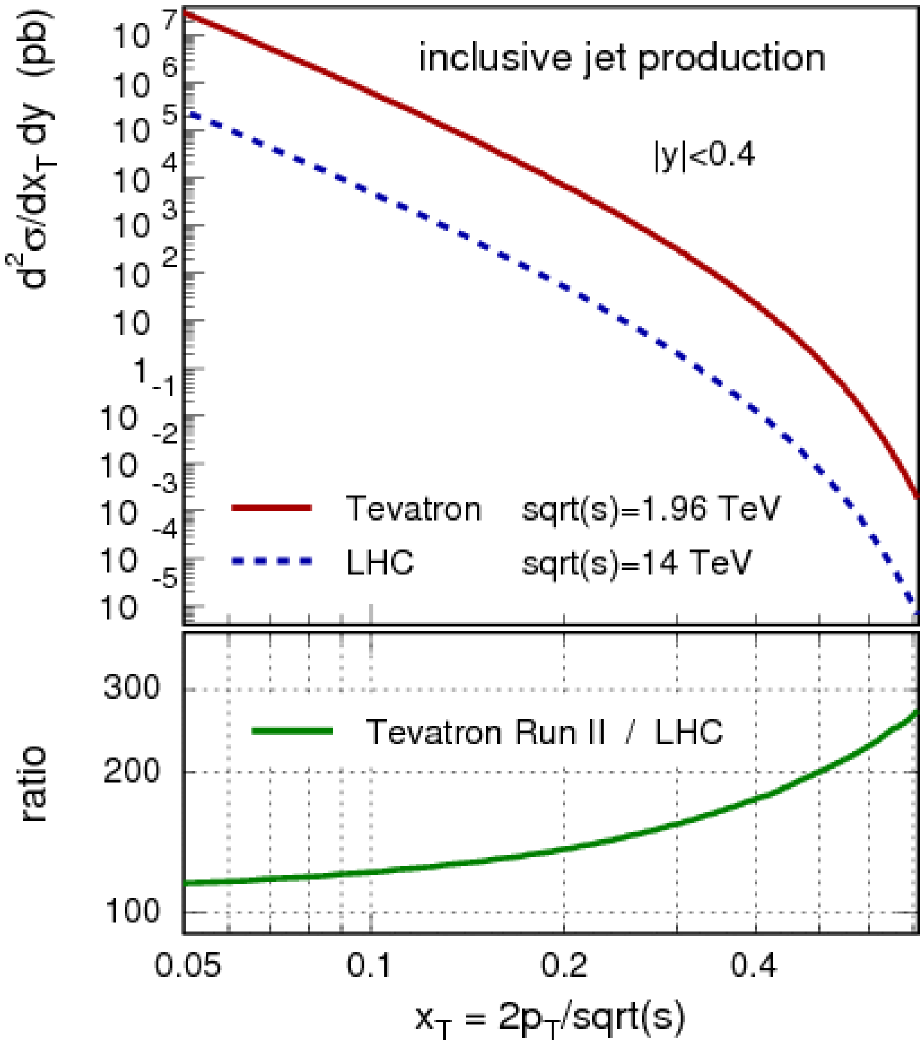
Exp. uncertainties < PDF uncertainties

Benefit from:

- high luminosity in run II
- increased run II cm energy → high p_T
- **hard work on jet energy calibration**



Incl. Jets: TeVatron vs LHC



PDF sensitivity:

compare jet cross section at fixed

$x_T = 2p_T / \mathrm{sqrt}(s)$

Tevatron (ppbar)

>100x higher cross section @ all x_T

>200x higher cross section @ x_T>0.5

LHC (pp)

- need more than 1600fb^{-1} luminosity to compete with Tevatron @8fb^{-1}
- more high-x gluon contributions
- but more steeply falling cross sect. at highest p_T (=larger uncertainties)

Tevatron results will dominate high-x gluon for some years …

Dijet angular distribution

Analysis variable:

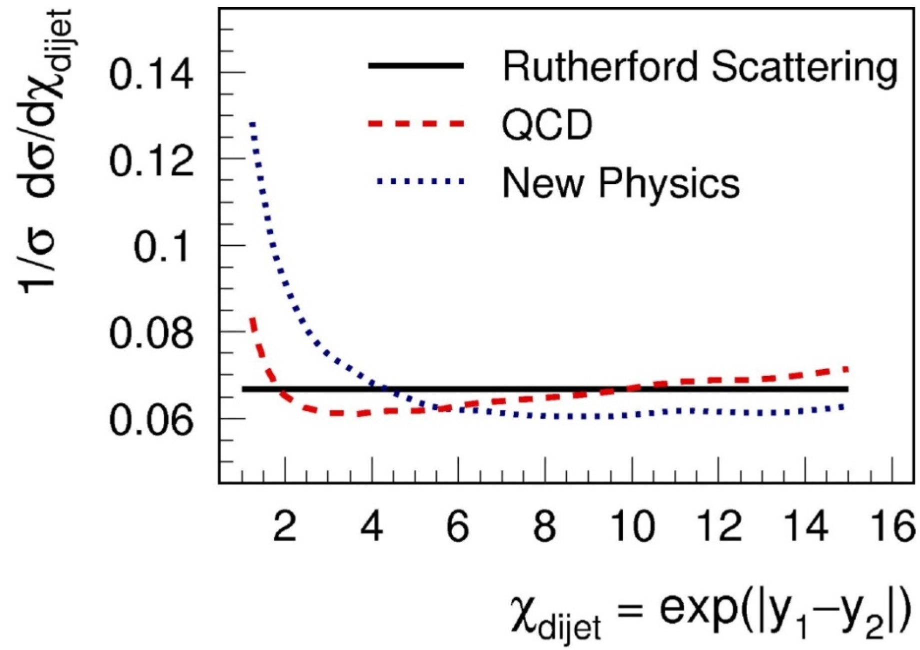
$$\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$$

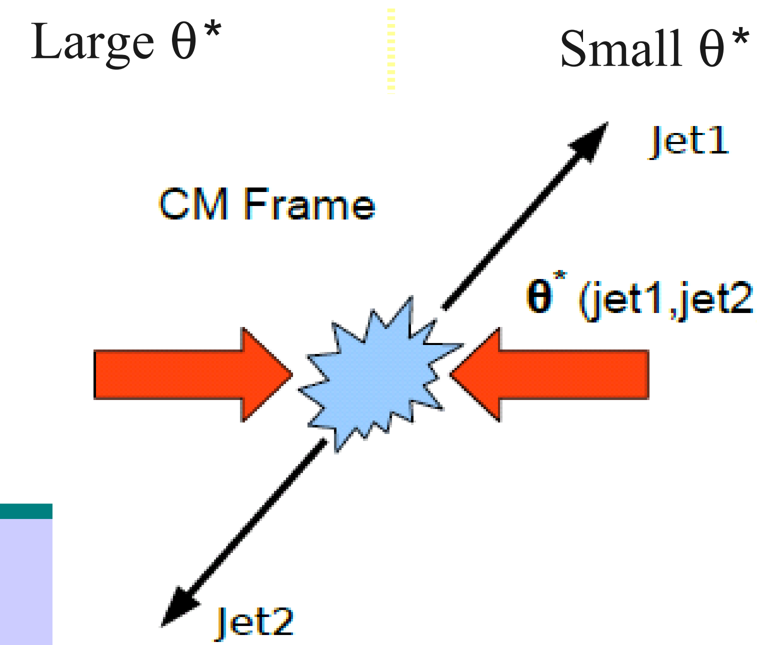
at LO, related to parton CM scattering angle

$$\chi_{\text{dijet}} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

- flat for Rutherford scattering
- relatively flat shape in QCD
- small PDF dependence
- enhancement at low χ_{dijet} for new physics
  - quark compositeness
  - ADD large extra dimensions
  - TeV^{-1} extra dimensions

(increased scattering at large angles)





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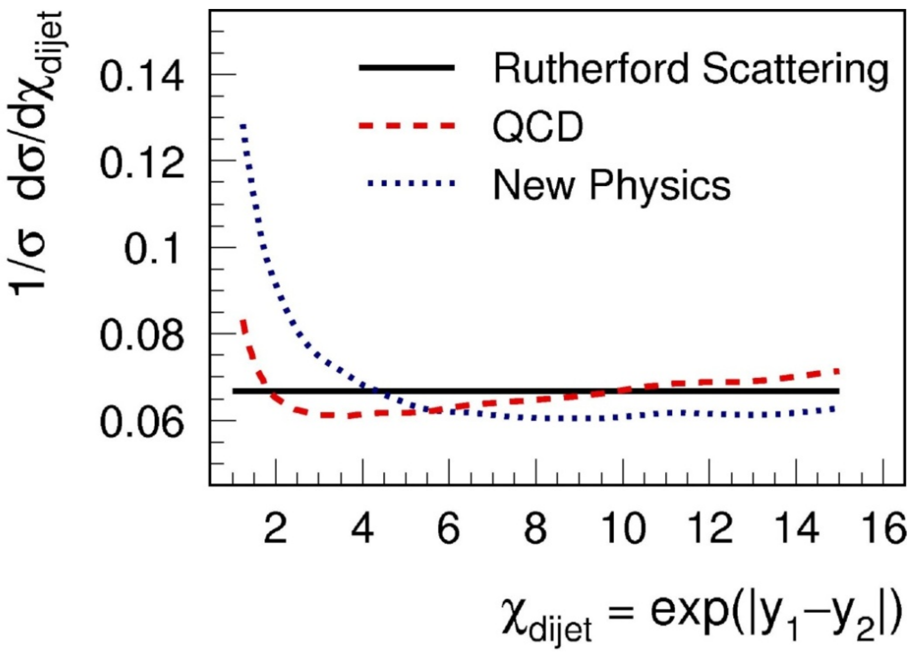
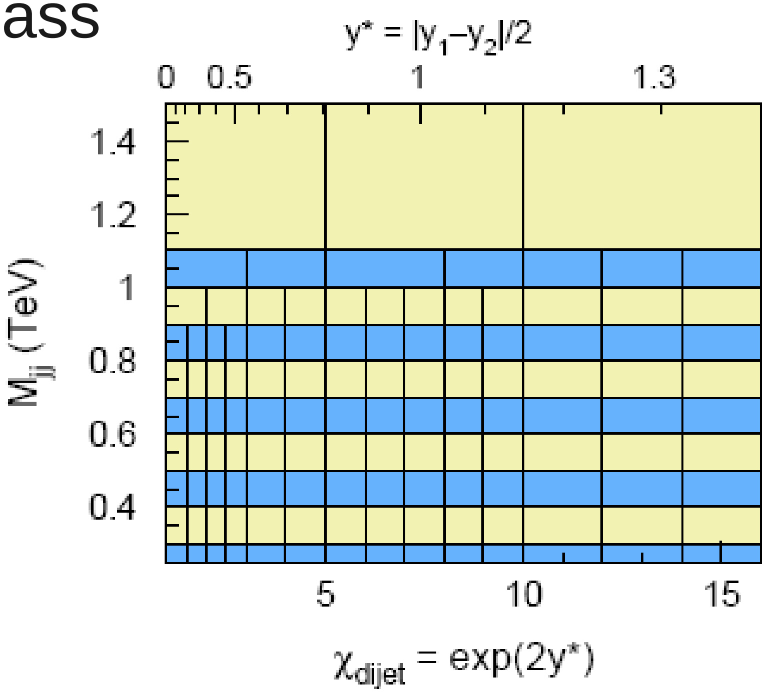


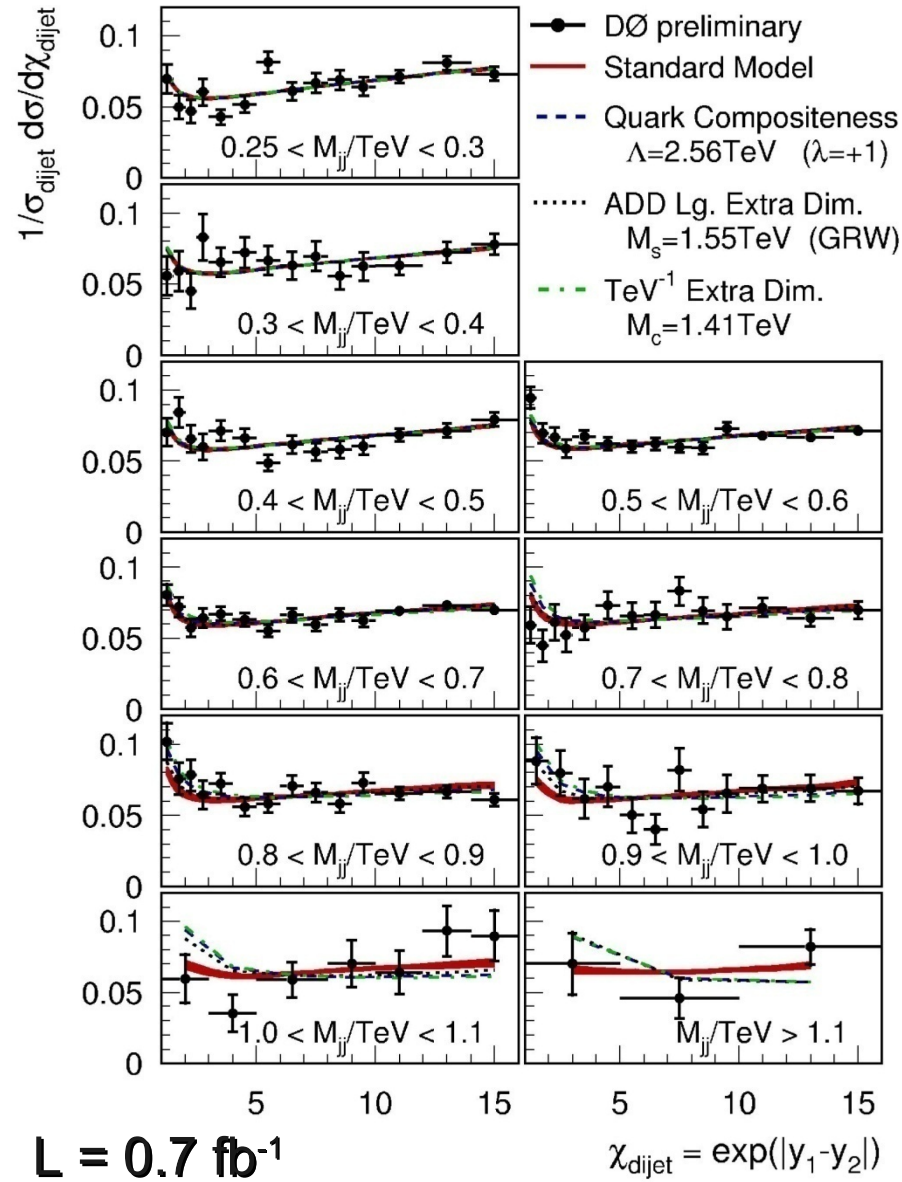
Large θ* Small θ*

examine normalized distribution $\frac{1}{\sigma}\frac{d\sigma}{d\chi_{\text{dijet}}}$
to reduce experimental and theoretical uncertainties

Dijet angular distribution

- Take data with single trigger (avoid correlated trigger biases)
- Correct distributions to particle level
- Analyze data in ranges of dijet invariant mass





First measurement of angular distributions of a scattering process above 1 TeV

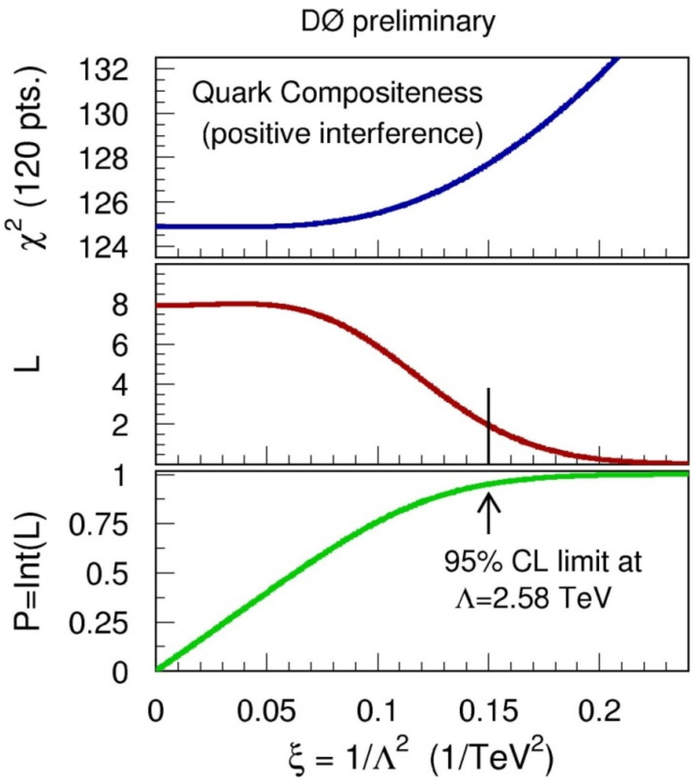
Good agreement w/ QCD, set limits on new physics models

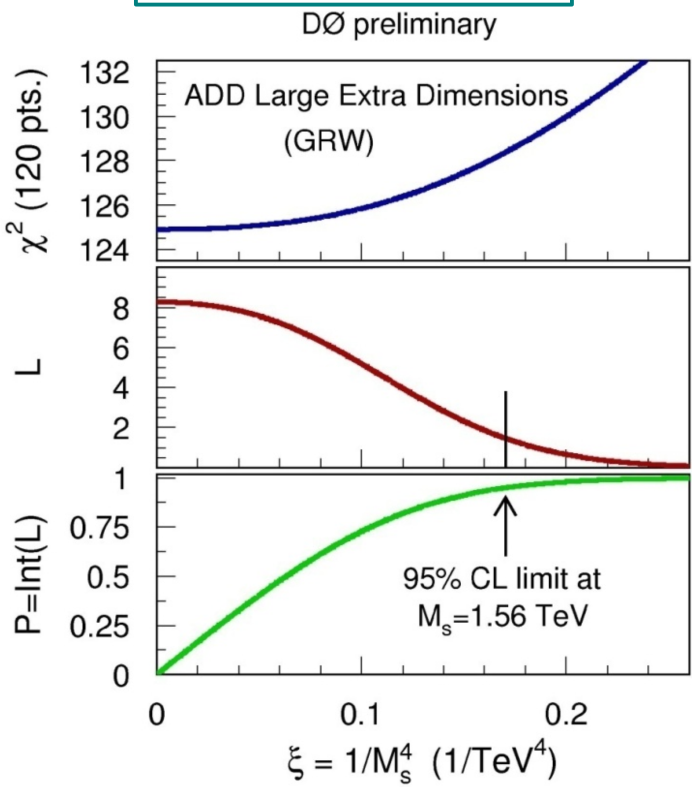
Dijet angular distribution

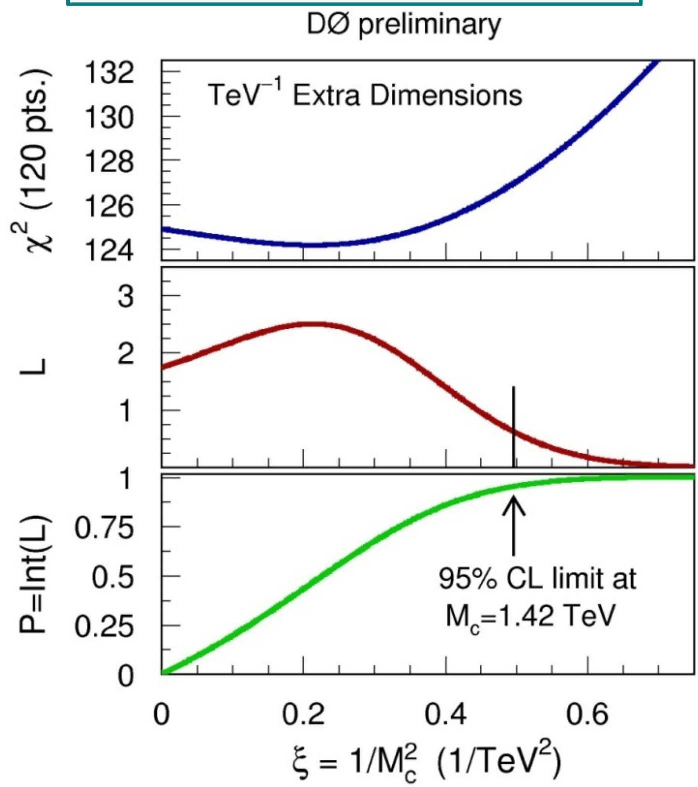
Quark Compositeness:
$\Lambda = 2.58$ TeV

A.D.D. LEDs:
$M_S = 1.56$ TeV

TeV^{-1} Extra Dims.:
$M_C = 1.42$ TeV







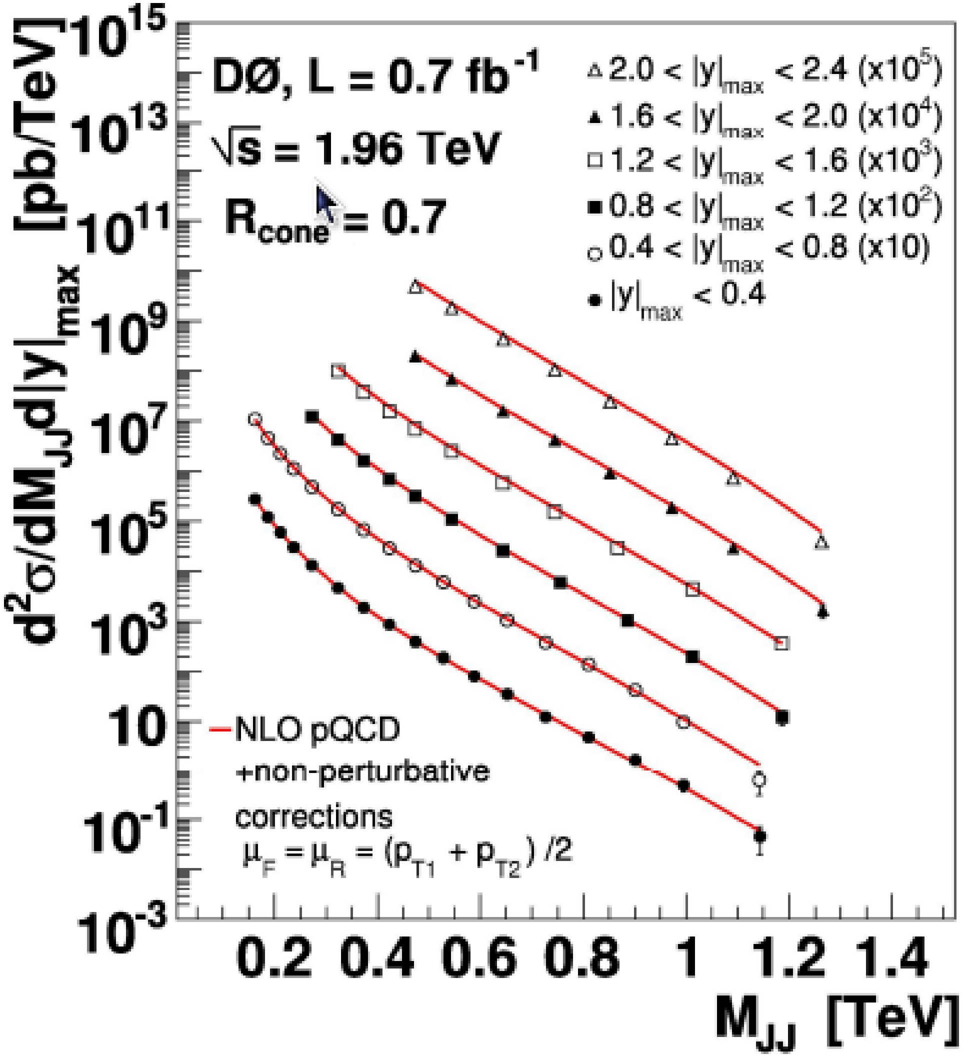
Most stringent limit

Most stringent limit from single process at hadron collider

Strongest limit from a hadron collider

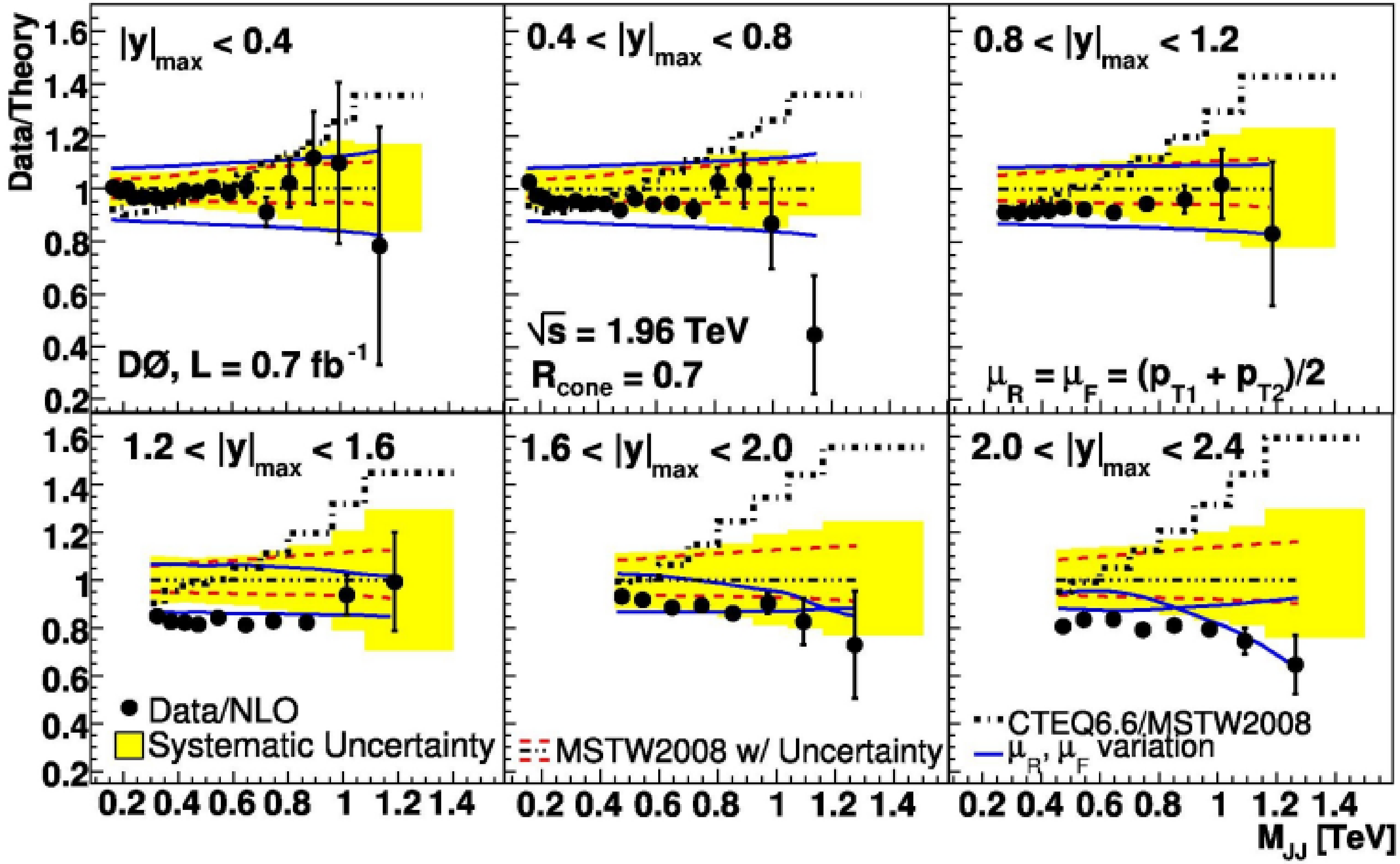
Dijet cross section

- 2 jets with p_T>40 GeV
- $|y|_{max}$, the absolute rapidity of the jet with the largest y of the 2 leading p_T jets
- M_{jj}, dijet invariant mass
- M_{jj} bins: twice the mass resolution, efficiency and purity above 50%



- Uncertainty comparable to PDF, μ_R and μ_F uncertainties
- MSTW2008NLO PDFs are favored by measurement

Compare to NLO predictions



- Note that MSTW2008 uses RunII data in PDF fits
- Good agreement in the central region
- $40 - 60\%$ difference between MSTW2008 and CTEQ6.6

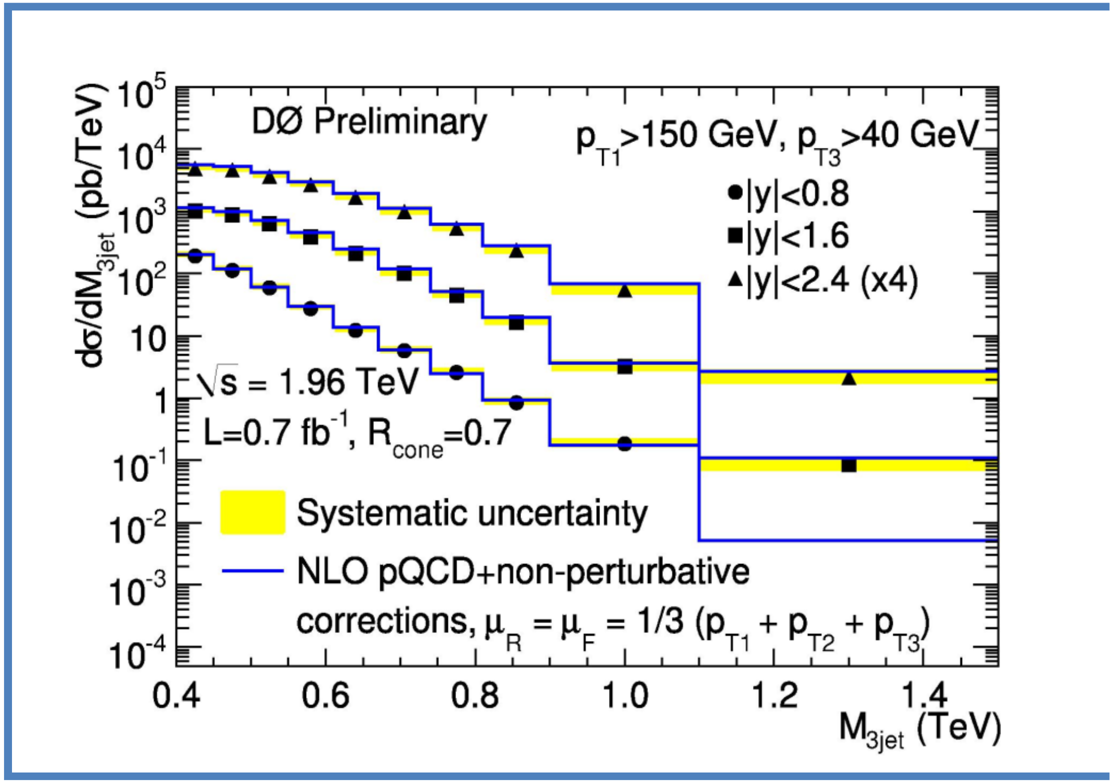
Multijets: 3-jet mass

First measurement of 3-jet cross section at Tevatron

- Require >= 3 jets in the event
- Jet 1 p_T > 150 GeV
- Jet 2,3 p_T > 40 GeV
- Jets separated by $\Delta R > 1.4$ = 2*Rcone
- Measurement performed in:
  - rapidity intervals $|y| < 0.8, 1.6, 2.4$
  - p_T ranges of the 3rd jet: p_TJet3 > 40, 70, 100 GeV

Compare data to NLO pQCD

Rapidity Dependence



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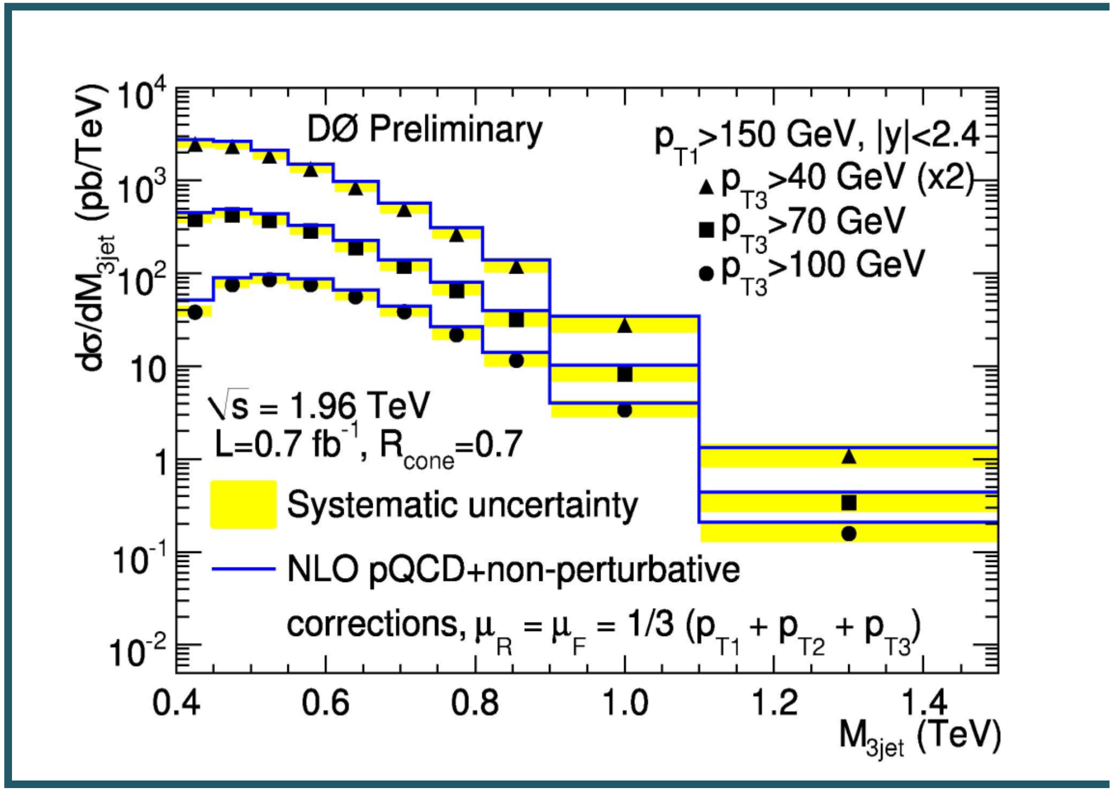
Compare data to NLO pQCD

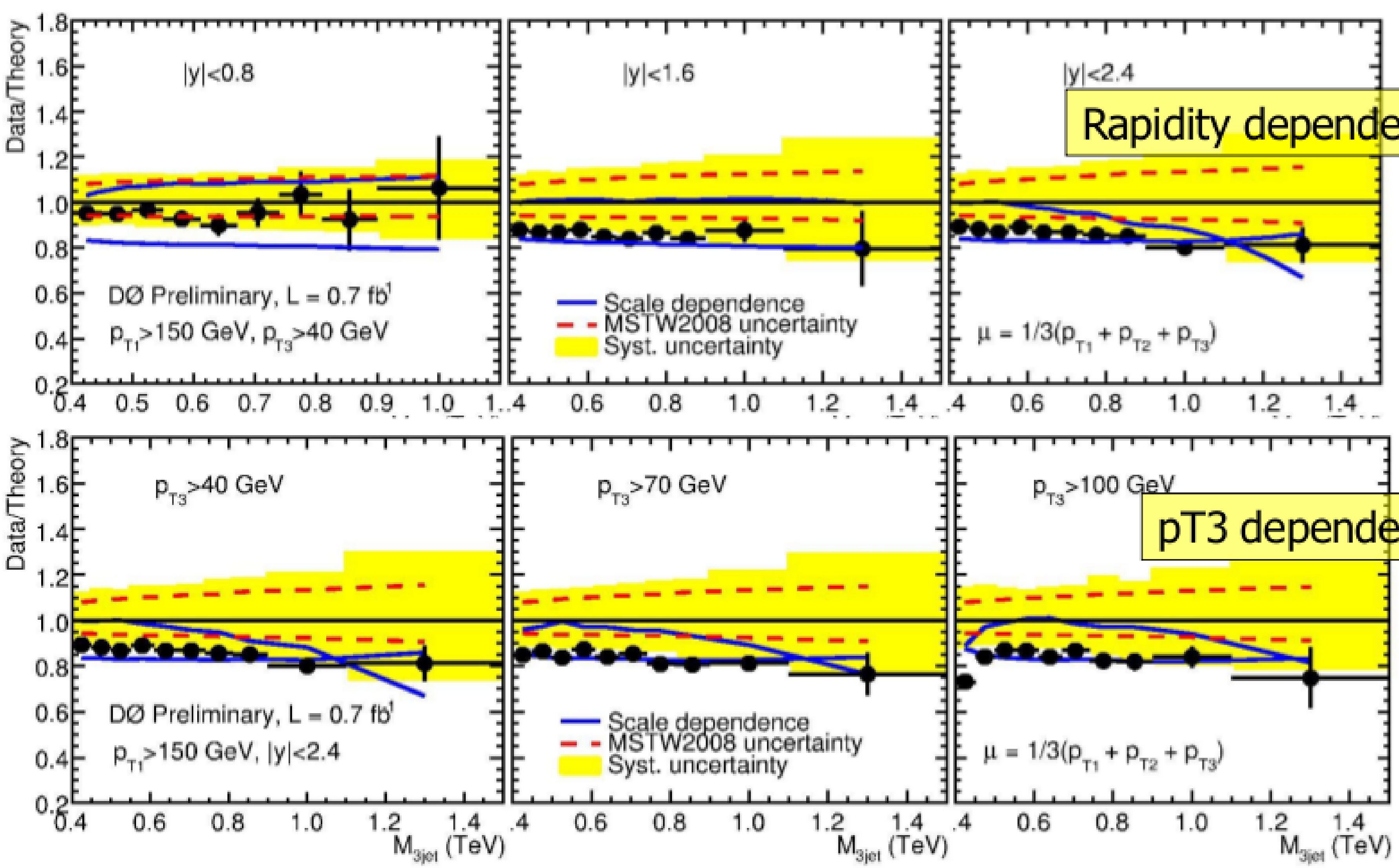
pTJet3 Dependence



$$\frac{d\sigma}{dM_{3\text{jet}}} = \frac{1}{L \cdot \Delta M_{3\text{jet}}} \cdot \left(\sum_{i=1}^{N_{\text{evt}}} \frac{1}{\epsilon_{\text{v}}^{i}} \right) \cdot C_{\text{unsmear}}$$

Unsmeared cross section, a first!

3-jet CS vs NLO



Rapidity dependence

pT3 dependence

Well described by pQCD: 1st test 3-jet NLO cross section!

R3/2: 3-jet/2jet cross section ratio

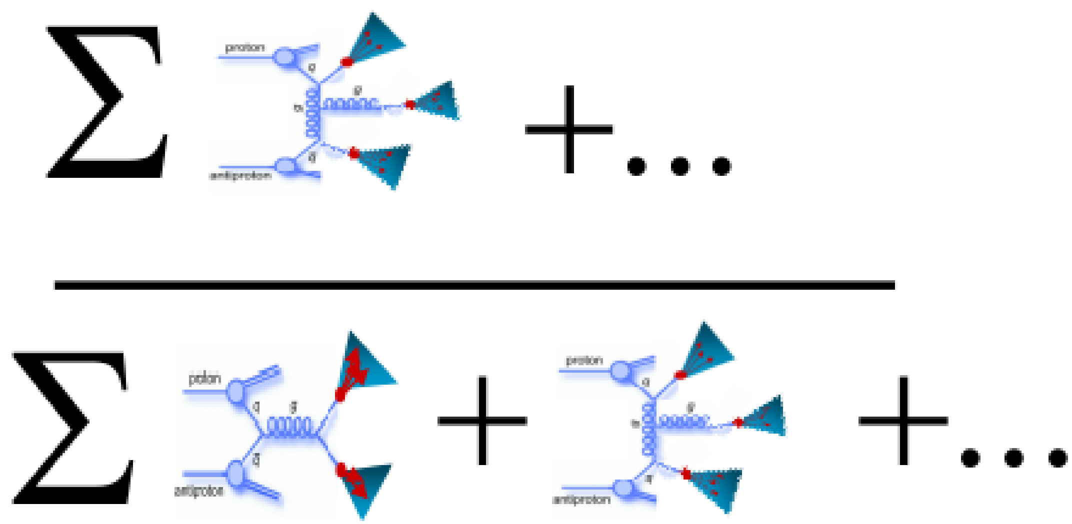
Goal: test pQCD (and α_s) independent of PDFs

Conditional probability:

$R_{3/2}$

$= P(3^{rd} \text{ jet} \mid 2 \text{ jets})$

$= \sigma_{3\text{-}jet} / \sigma_{2\text{-}jet}$



- Probability to find a third jet in an inclusive dijet event
- Sensitive to α_s (3-jets: α_s^3 / 2-jets: α_s^2)
- (almost) independent of PDFs

R3/2: 3-jet/2jet cross section ratio

Measure as function of two momentum scales:

- p_{Tmax} : common scale for both $\sigma_{2\text{-}jet}$ and $\sigma_{3\text{-}jet}$
- p_{Tmin} : scale at which 3rd jet is resolved ($\sigma_{3\text{-}jet}$ only)

Sensitive to α_s at the scale p_{Tmax}

→ probe running of α_s in Tevatron energy regime → up to 500 GeV

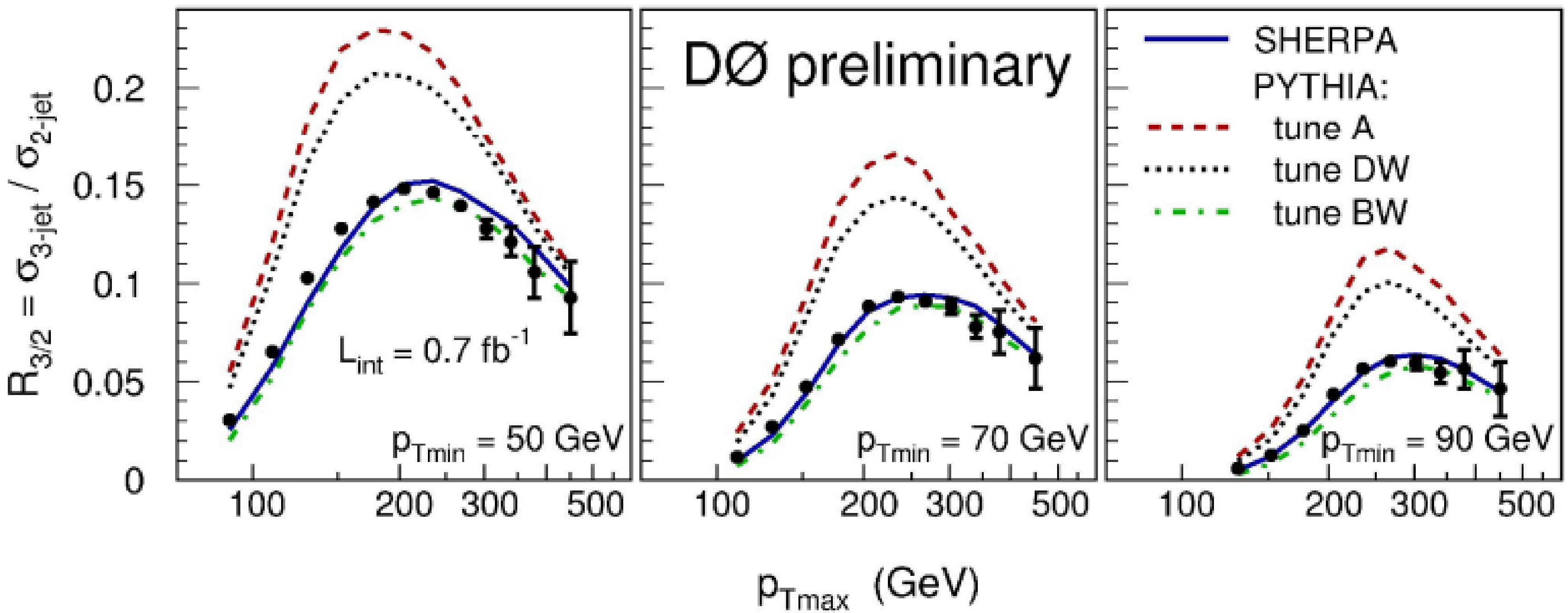
Details:

- inclusive *n*-jet samples (*n*=3,2) with *n* (or more) jets above p_{Tmin}
- $|y|<2.4$ for all *n* leading p_T jets
- $\Delta R_{jet,jet} > 1.4$ (insensitive to overlapping jet cones)
- study p_{Tmax} dependence for different p_{Tmin} of 50, 70, 90 GeV

→ Measurement of $R_{3/2}(p_{Tmax}\,;\,p_{Tmin})$

Cross section corrections give systematic uncertainties at 2-6% level!

R3/2: 3-jet/2jet cross section ratio



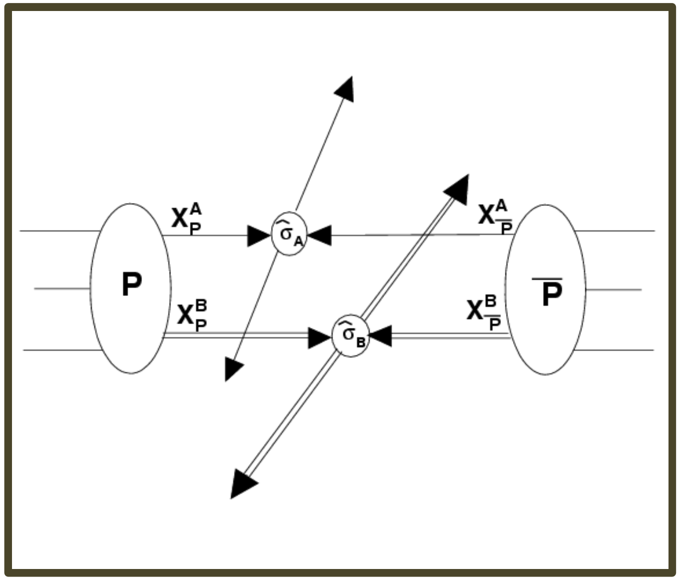
SHERPA: good description (default version w/ MSTW2008LO PDFs)

PYTHIA: huge dependence on tune

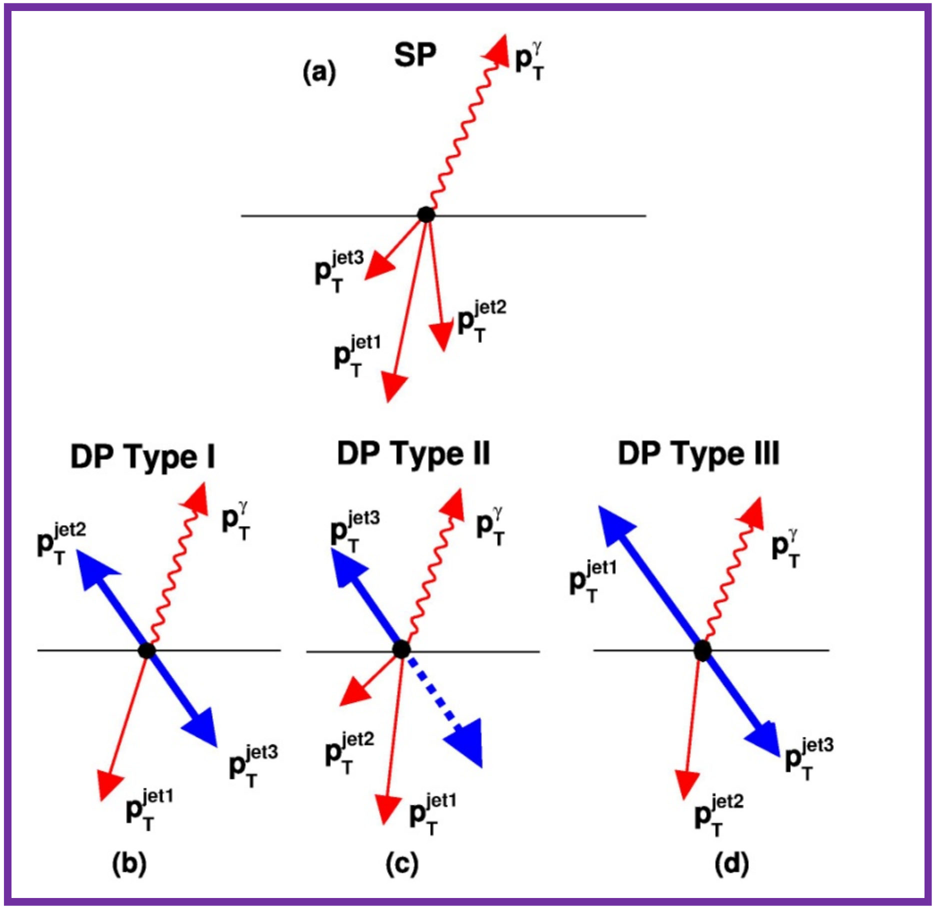
- Reasonable description by tune BW
- Popular tunes A, DW → totally off

Maybe: extract strong coupling → up to p_T>400 GeV (yet untested) gamma+3-jets

Double Parton Interactions



$$\sigma_{DP} = \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$



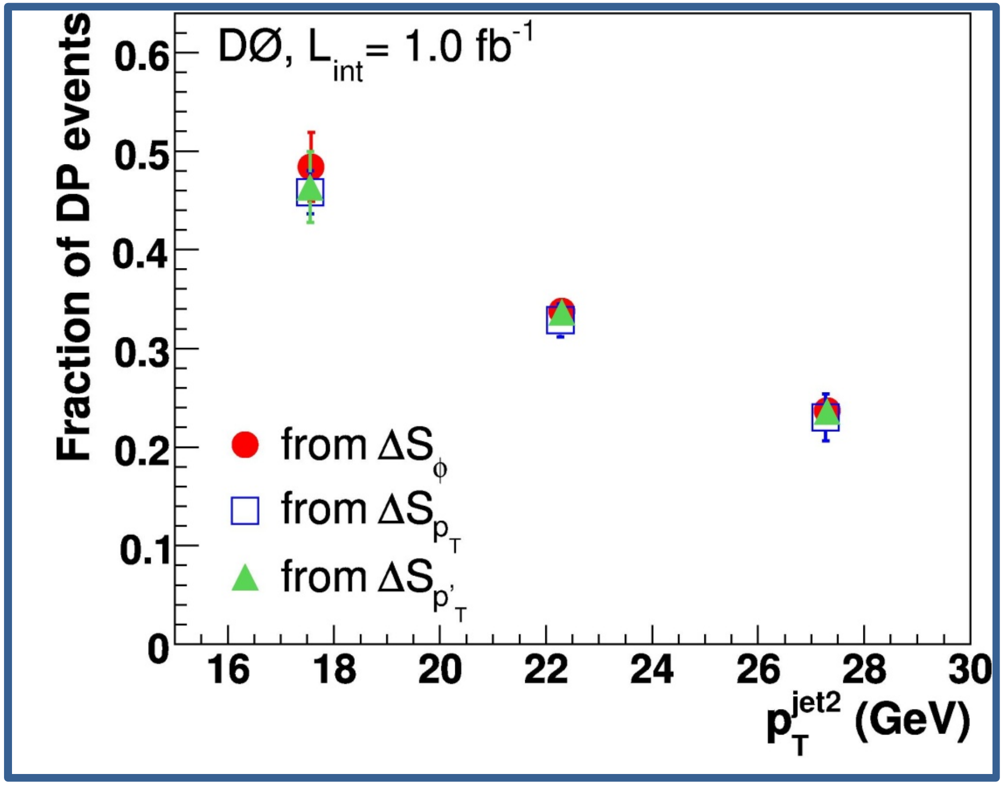
Scattering of two parton pairs in a collision

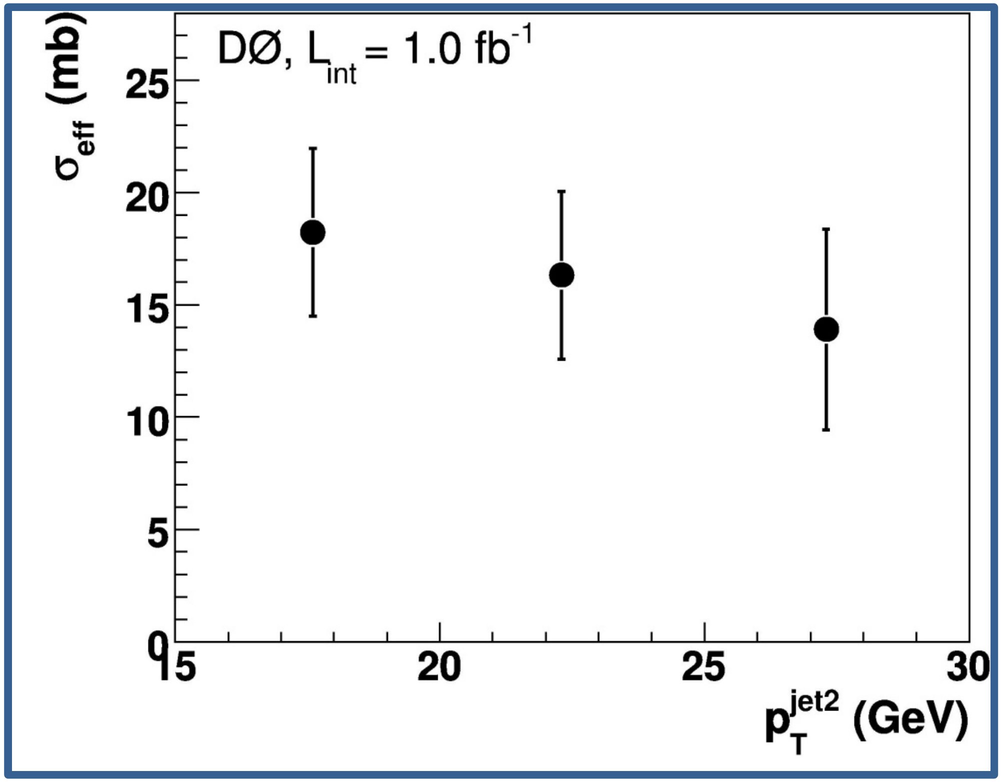
σeff: a measure of effective size of interaction region

Increasingly important for backgrounds to X+n-jets

Contains information on the spatial distribution of partons
Uniform: Large σeff :: small σDP
Clumpy : Small σeff :: large σDP

Double Parton Results





DØ: PRD 81, 052012 (2010)

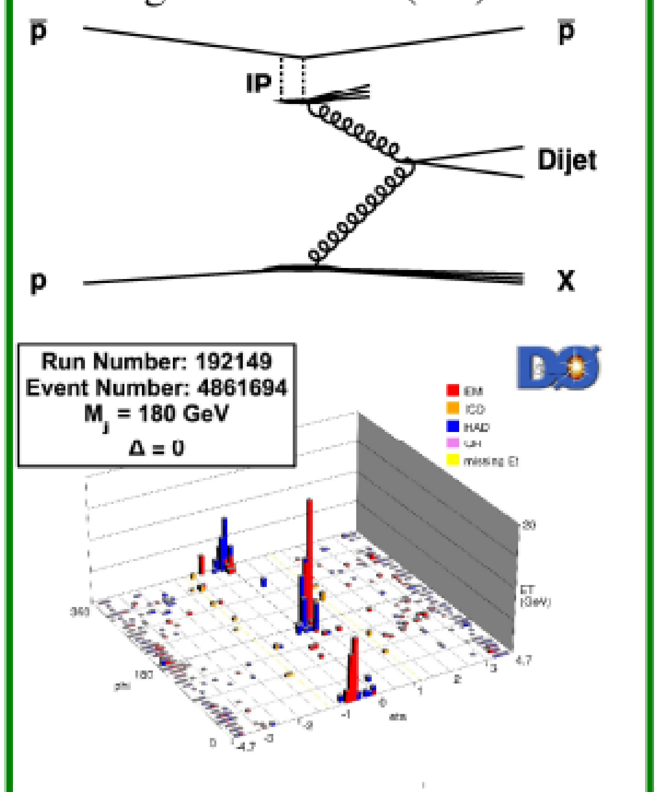
Average σeff = 16.4 ± 0.3(stat) ± 2.3 (syst) mb

In agreement with previous CDF measurements: PRD 47, 4857 (1993); PRL 79, 584 (1997)

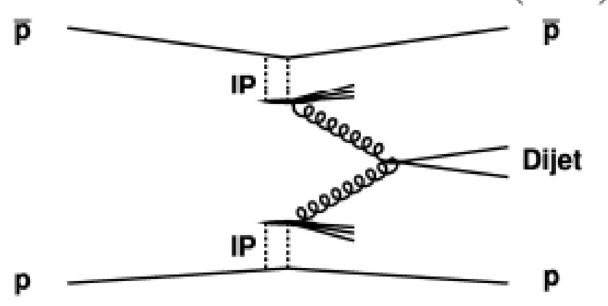
Exclusive jet production

- Events identified by gap devoid of activity in forward region
  - Exchange of colorless object (Pomeron)
- Proposed as Higgs search channel at LHC at very large masses

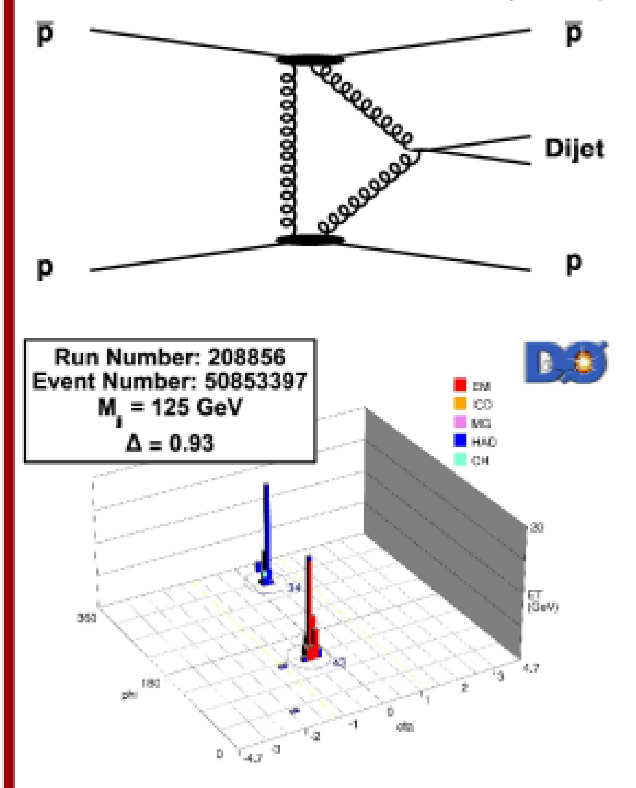
Single diffraction(SD)



Inclusive double Pomeron(IDP)

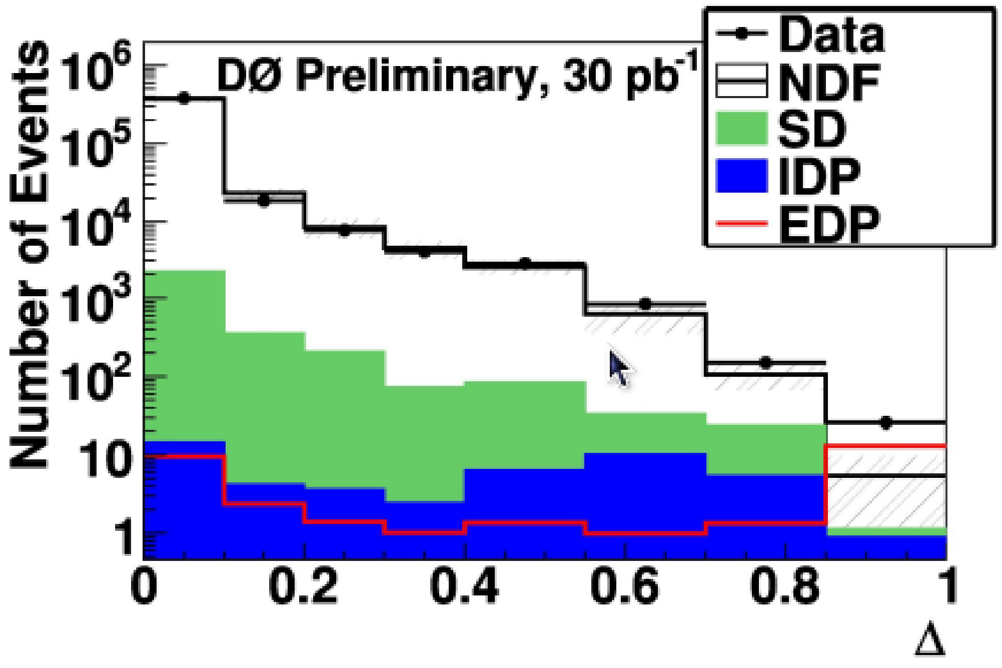


Exclusive diffractive(EDP)

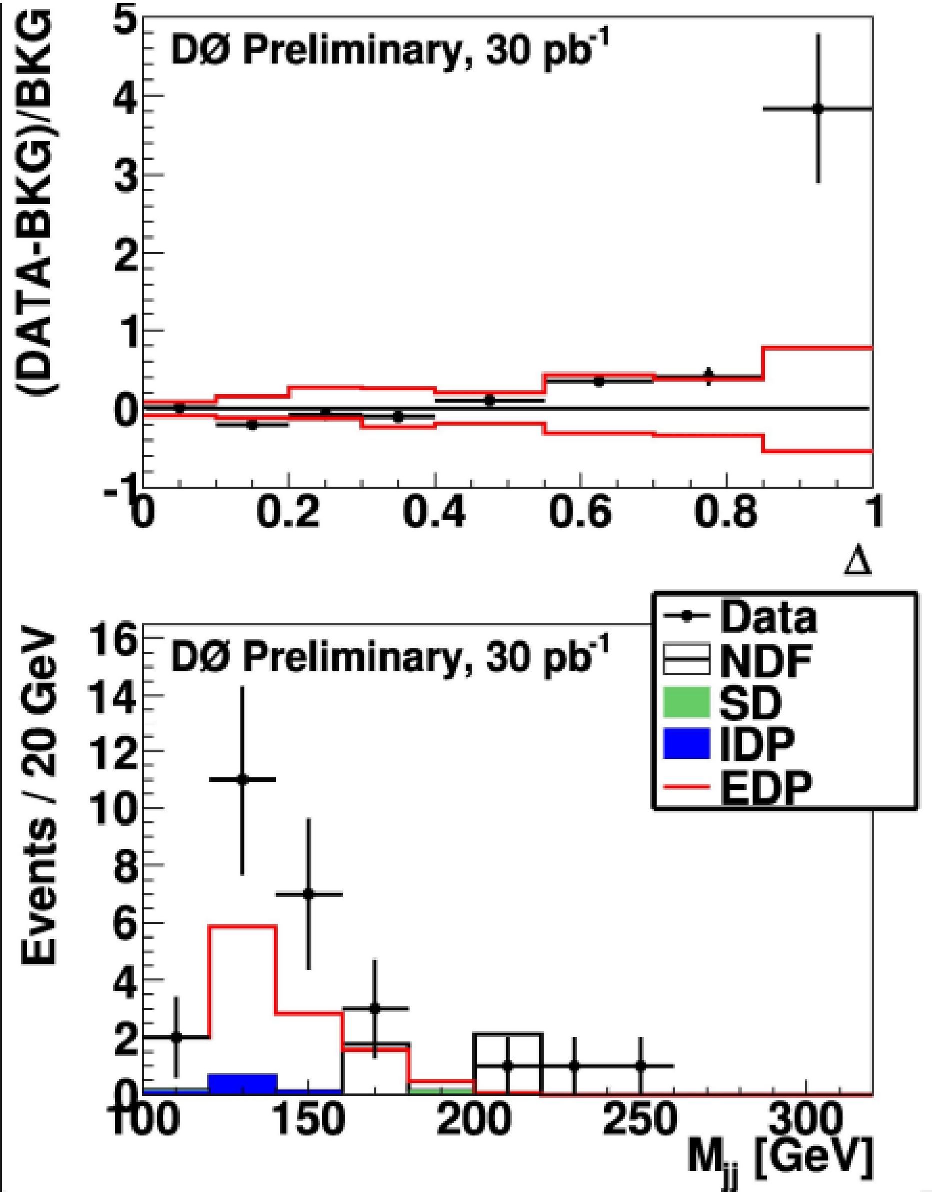


Exclusive jet production

- 2 back-to-back central jets (|y|<0.8 and $\Delta\varphi > 3.1$rad)
  - p_{T1}>60GeV and p_{T2}>40 GeV, Dijet invariant mass >100 GeV
- Low instantaneous luminosity: avoid multiple interactions
- Discriminant: $$\Delta = \frac{1}{2}\exp\Big(-\sum_{2.0<|\eta|\leq 3.0} E_T/\mathrm{GeV}\Big) + \frac{1}{2}\exp\Big(-\sum_{3.0<|\eta|<4.2} E_T/\mathrm{GeV}\Big)$$



Exclusive jet production



- 26 candidate events, to bkg prediction of $5.4^{+4.2}_{-2.9}$ in excess bin $\Delta > 0.85$
- Excess significance: 4.1σ

Highest mass observation of exclusive processes

α_s in QCD

The coupling strength, α_s is scale dependent, $\alpha_s(\mu_R)$

- Its numerical value is not predicted in QCD
- But **R**enormalization **G**roup **E**quation (RGE), predicts μ_R-dependence

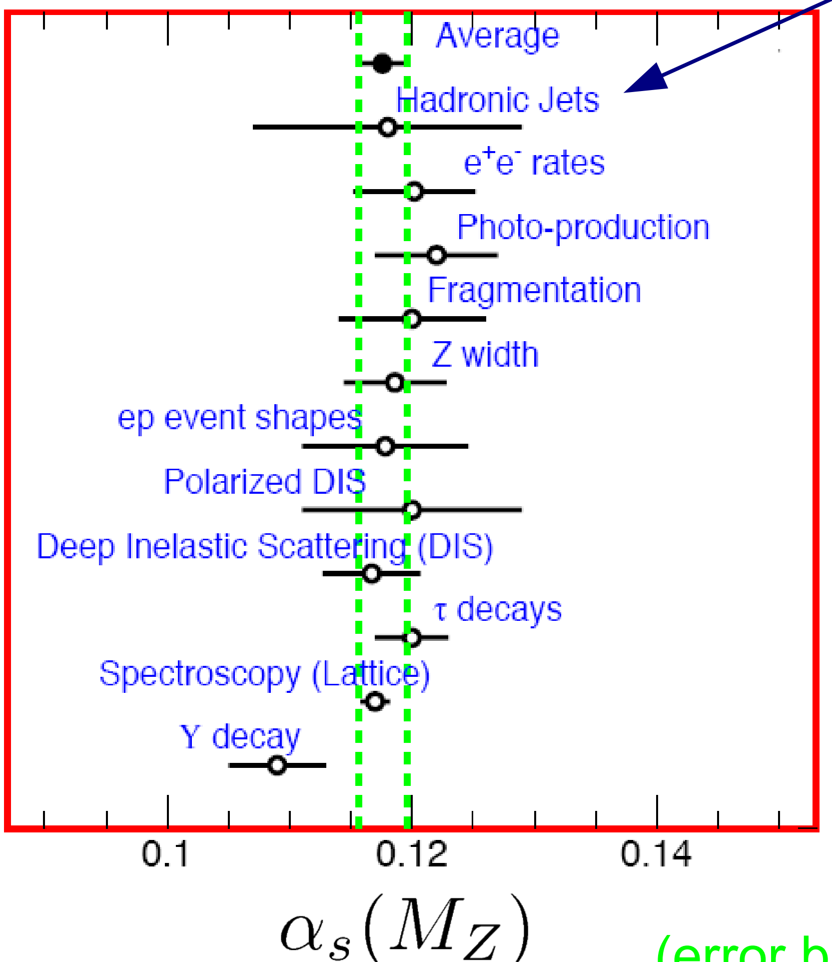
- Measure values in experiment and test RGE compatibility
  - For jet production take μ_R = jet p_T
  - Values of $\alpha_s(\mu_R)$ can be compared at a common scale, typically $\alpha_s(M_Z)$, by using RGE

e.g. for two loop solution to RGE

$$\alpha_s(M_Z) = \frac{\alpha_s(\mu_R)}{1 + \alpha_s(\mu_R)(b_0 + b_1\alpha_s(\mu_R))ln(\mu_R/M_Z)}$$

Recent past status of α_s measurements

2008 Review of
Particle Physics



Large uncertainty associated with "Hadronic Jets"

Previously not very competitive with other determinations

Now have the tools to substantially improve this result.

- More and better data
- More precise theory calculations

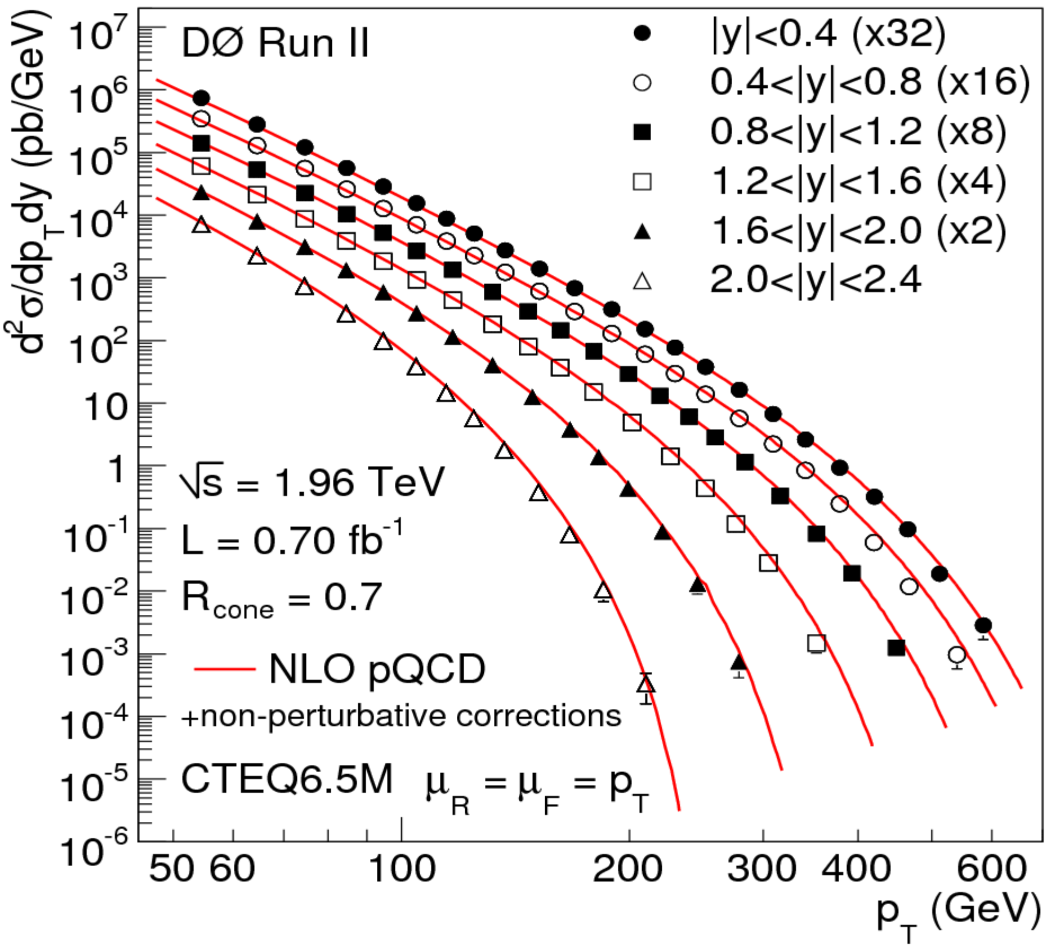
DØ data allow new precision measurements!

(error band includes theory)

Extraction of α_s from inclusive jet CS

$$\sigma^{jet}_{pert}(\alpha_s) = \left(\sum_n \alpha_s^n c_n\right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

Most precise measure of inclusive jet production



Phys. Rev. Lett. 101, 062001 (2008)

Renormalization Group Eqn uniquely relates $\alpha_s(\mu_R)$, for arbitrary scale μ_r to $\alpha_s(M_Z)$

Express theoretical prediction as:

$$\sigma_{theory}(\alpha_s(M_Z)) = \sigma_{pert}(\alpha_s(M_Z)) \cdot c_{non-pert}$$

Contains α_s dependence in ME as well as implicit α_s dependence in the PDFs

Extraction of α_s from inclusive jet CS

Strategy: Determine best fit to data using χ^2 function

$$\chi^2(\xi, \vec{\epsilon}, \vec{\alpha}) = \sum_{i=1}^{npoints} \frac{\left[d_i - t_i(\xi, \vec{\alpha})\left(1 + \sum_j \delta_{ij}(\epsilon_j)\right)\right]^2}{\sigma^2_{i,stat} + \sigma^2_{i,uncorr.}} + \sum_j \epsilon_j^2 + \sum_k \alpha_k^2$$

ξ : fit parameter, $\alpha_s(M_Z)$
$\overline{\alpha}$: systematic parameters for calculation (PDFs, non-pert. corrs)
$\overline{\epsilon}$: systematic parameters on measurement (luminosity, jet E scale, etc.)

Minimize χ^2 wrt variable nuisance parameters ($\overline{\epsilon}$,$\overline{\alpha}$). These vary, but not freely, due to constraints from prior knowledge of systematics.

Uncertainties due to renormalization and factorization scales can not be treated as normal distributions. Instead repeat fit with $\mu_{r,f} = 0.5p_T$, $2.0p_T$ and use difference with central result, $\mu_{r,f} = p_T$.

Extraction of α_s from inclusive jet CS

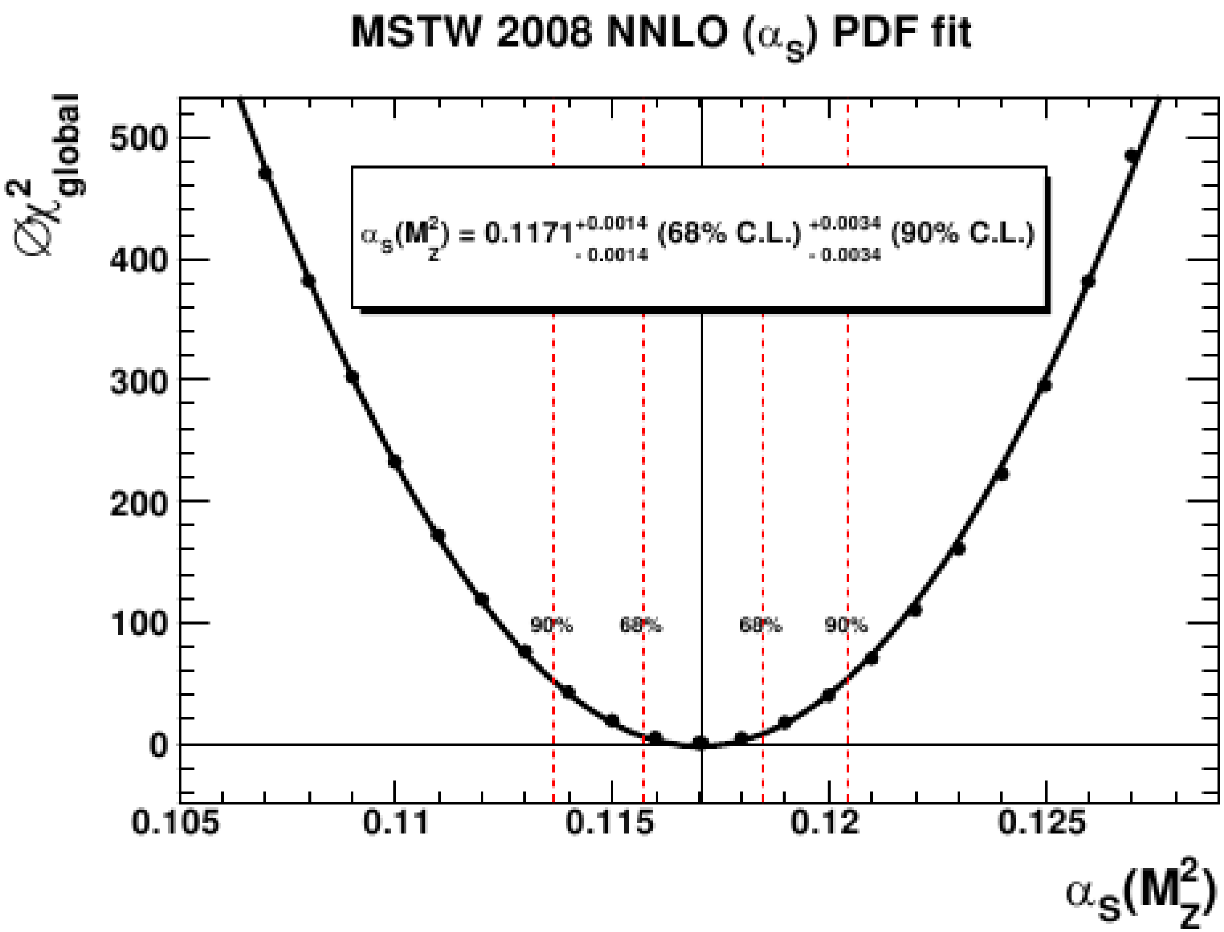
Strategy: Determine best fit to data using χ^2 function

$$\chi^2(\xi,\vec{\epsilon},\vec{\alpha}) = \sum_{i=1}^{npoints} \frac{\left[d_i - t_i(\xi,\vec{\alpha})\left(1+\sum_j \delta_{ij}(\epsilon_j)\right)\right]^2}{\sigma^2_{i,stat}+\sigma^2_{i,uncorr.}} + \sum_j \epsilon_j^2 + \sum_k \alpha_k^2$$

Contains ME and PDFs. Minimizing for ξ = $\alpha_s(M_Z)$ requires knowledge of PDF sets including α_s dependence. Use MSTW2008, provides fits for 21 values of $\alpha_s(M_Z)$ in range 0.110--0.130

ξ : fit parameter, $\alpha_s(M_Z)$
$\underline{\alpha}$: systematic parameters for calculation (PDFs, non-pert. corrs)
$\underline{\epsilon}$: systematic parameters on measurement (luminosity, jet E scale, etc.)

Choice of PDF models



MSTW2008 provides PDF fits in fine binning of alpha strong.

Allow for smooth interpolation of results to arbitrary $\alpha_s(M_Z)$ in range

NNLO accuracy.

arXiv:0905.3531v2
Eur.Phys.J.C64:653-680,2009

Theory

PQCD (two alternatives):

• NLO + added 2-loop threshold corrections (from Kidonakis/Owens)
  'NLO + 2-loop'

• NLO as cross check

Uncertainties due to scale dependence: $\mu_{r,f} = p_T$ (+ x0.5, x2.0)

Matched to appropriate PDF models

• MSTW2008NNLO for NLO + 2-loop

• MSTW2008NLO for NLO

NLO calculations performed using fastNLO (arXiv:hep-ph/0609285)

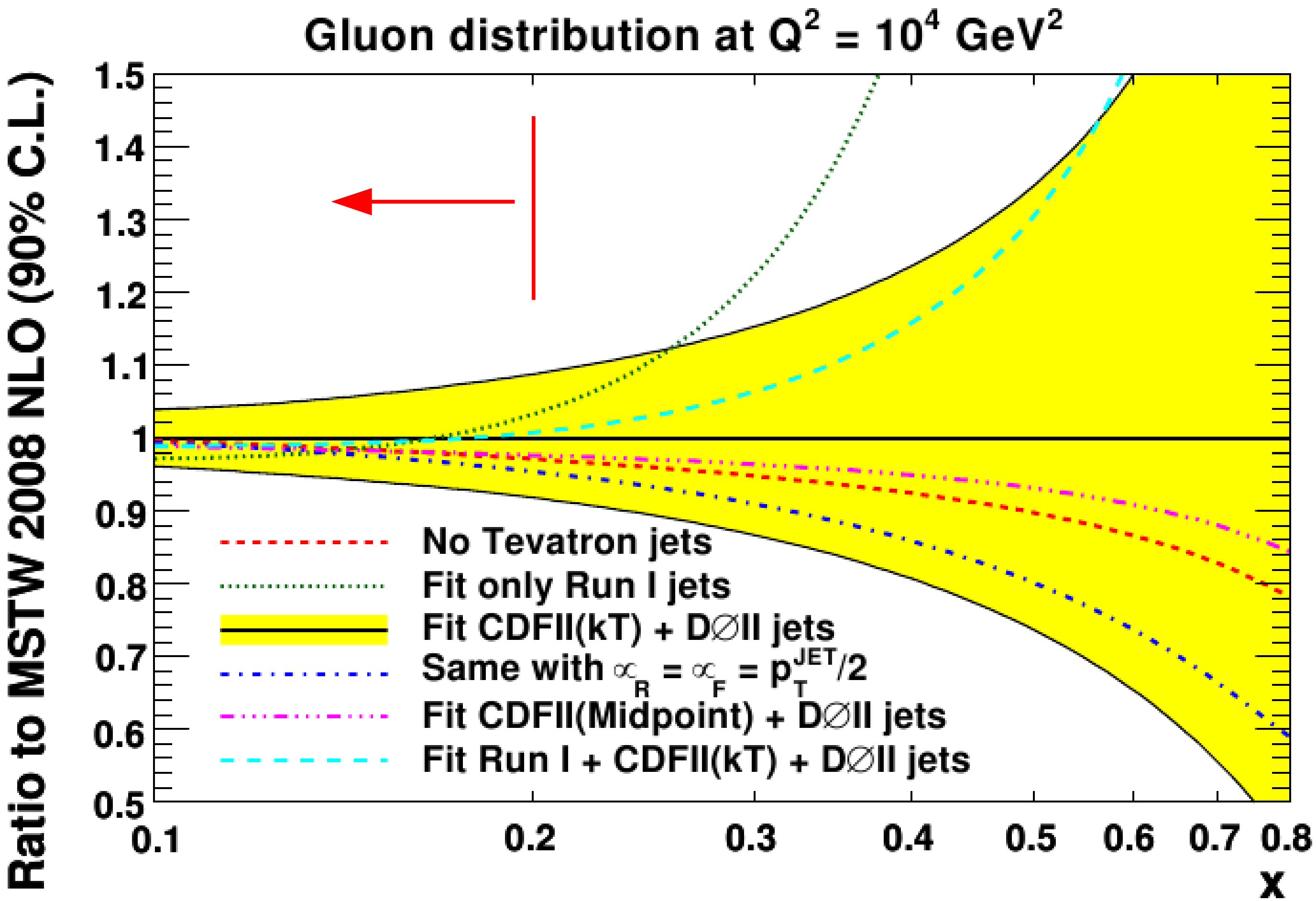
• Based on NLOJET++, provides fast recalculations wrt arbitrary PDFs

Non perturbative corrections (hadronization/underlying event)

• From PYTHIA (as with Inclusive Jets analysis)

Uncertainties: - 50% of correction, separately for each component

Minimizing correlations for data, PDFs



Precision Tevatron jet data currently dominate models for gluon densities at high-x

Minimize correlations between data and PDFs by restricting analysis to kinematic regions where impact of Tevatron data do not dominate PDF determination.

Parton-x sensitivity

At leading order, di-jet events access x-values of:

$$x_a = x_T \frac{e^{y_1} + e^{y_2}}{2} \qquad x_b = x_T \frac{e^{-y_1} + e^{-y_2}}{2} \qquad \text{with } x_T = \frac{2p_T}{\sqrt{s}}$$

Mapping is less clear in inclusive cross section data

x-value not fully constrained given a measurement bin of p_T, |y|

Full kinematics unknown, since we integrate over other jets

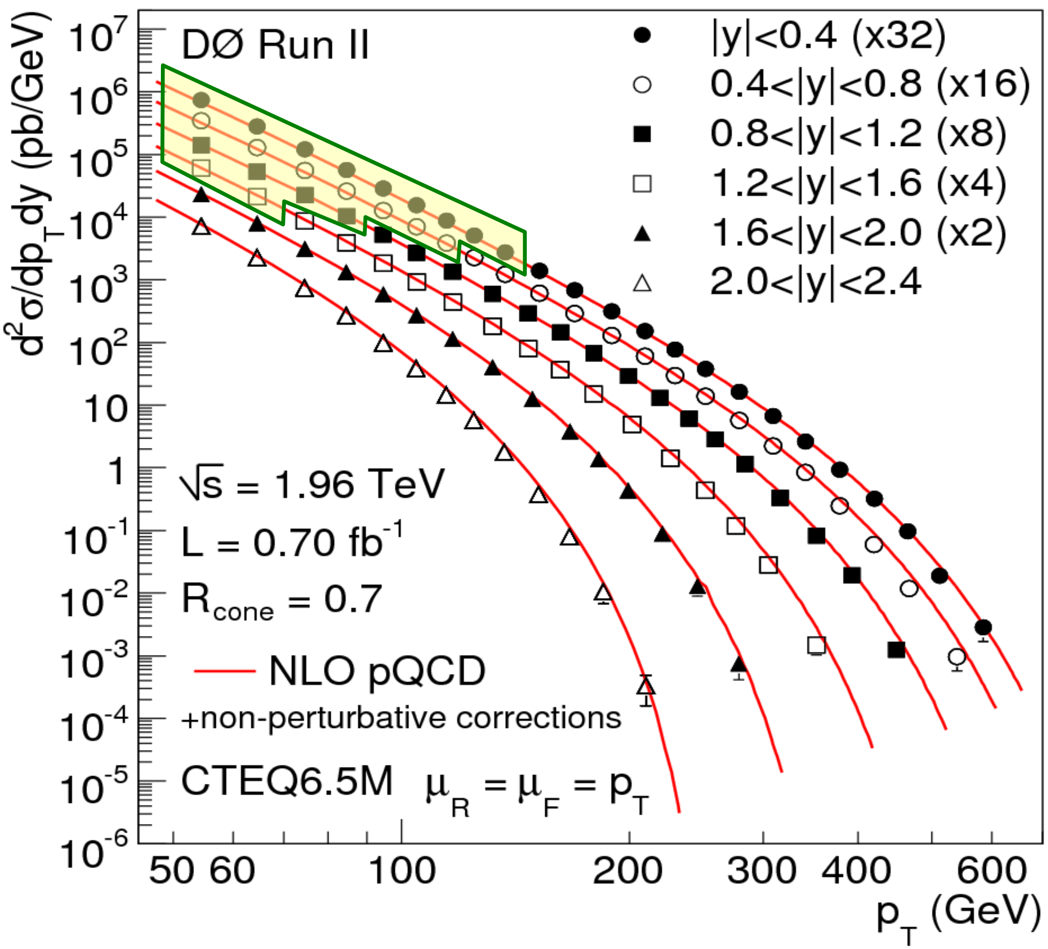
Construct 'test-variable' treating subleading jet(s) as a jet at |y|=0

$$\tilde{x} = x_T \cdot (e^{|y|} + 1)/2$$

Cut on $\tilde{x}$ to restrict accessible x-range

Systematics based on variations of cut value

Minimizing correlations for data, PDFs



Select points from inclusive cross section using approximate mapping having strong correlation with maximum parton-x in a 2-body collision

$$\tilde{x} = x_T \cdot (e^{|y|} + 1)/2$$

$$x_T = 2P_T/\sqrt{s}$$

Require $\tilde{x} < 0.15$

22 (of 110) data points $50 < p_T < 145$ GeV

corresponds to $x_{max} \sim 0.25$

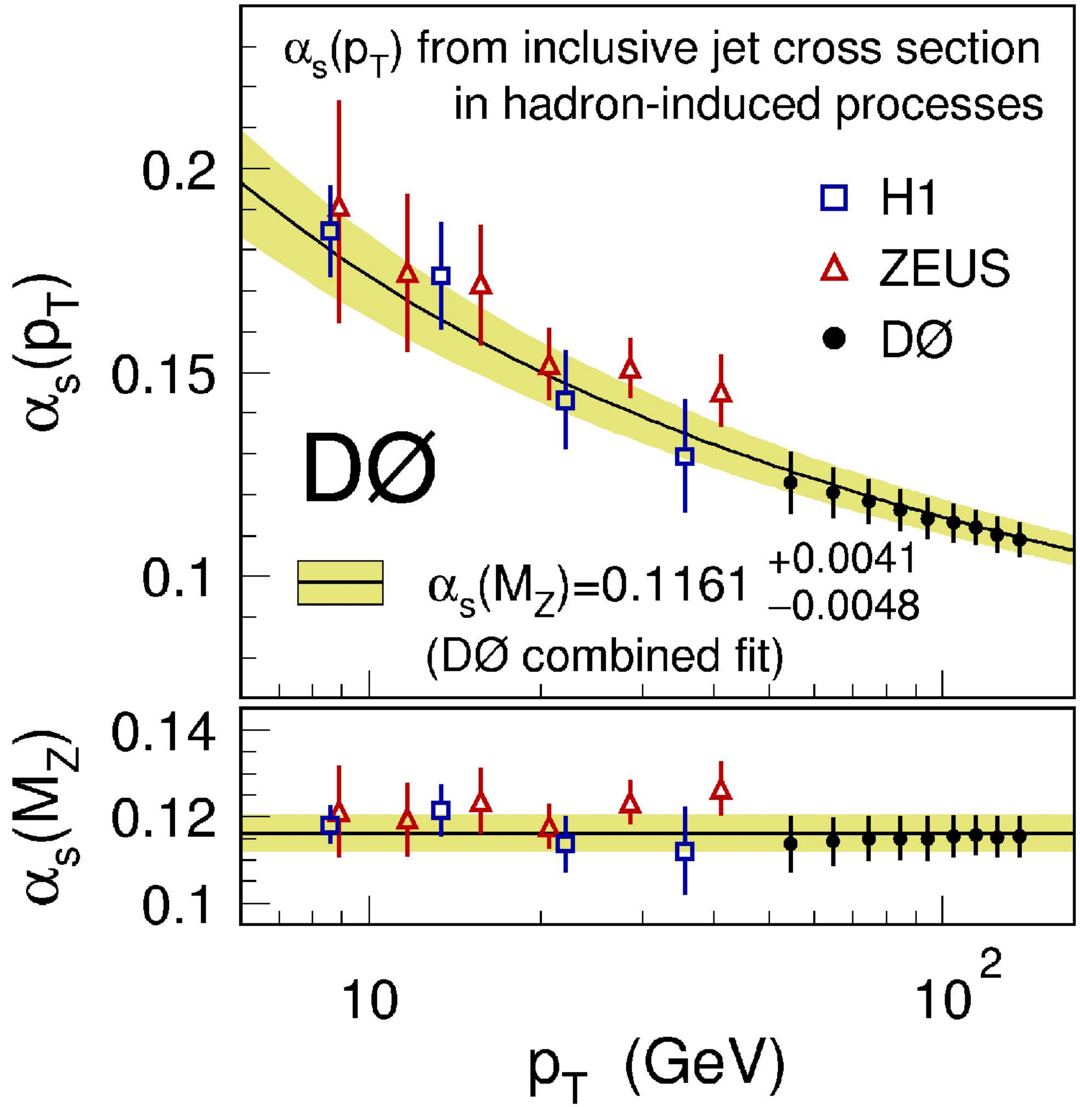
Results for α_s

- NLO Matrix Elements for five flavors, + additional 2-loop threshold corrections (reducing renormalization/ factorization scale dependence)

- MSTW2008 NNLO PDFs

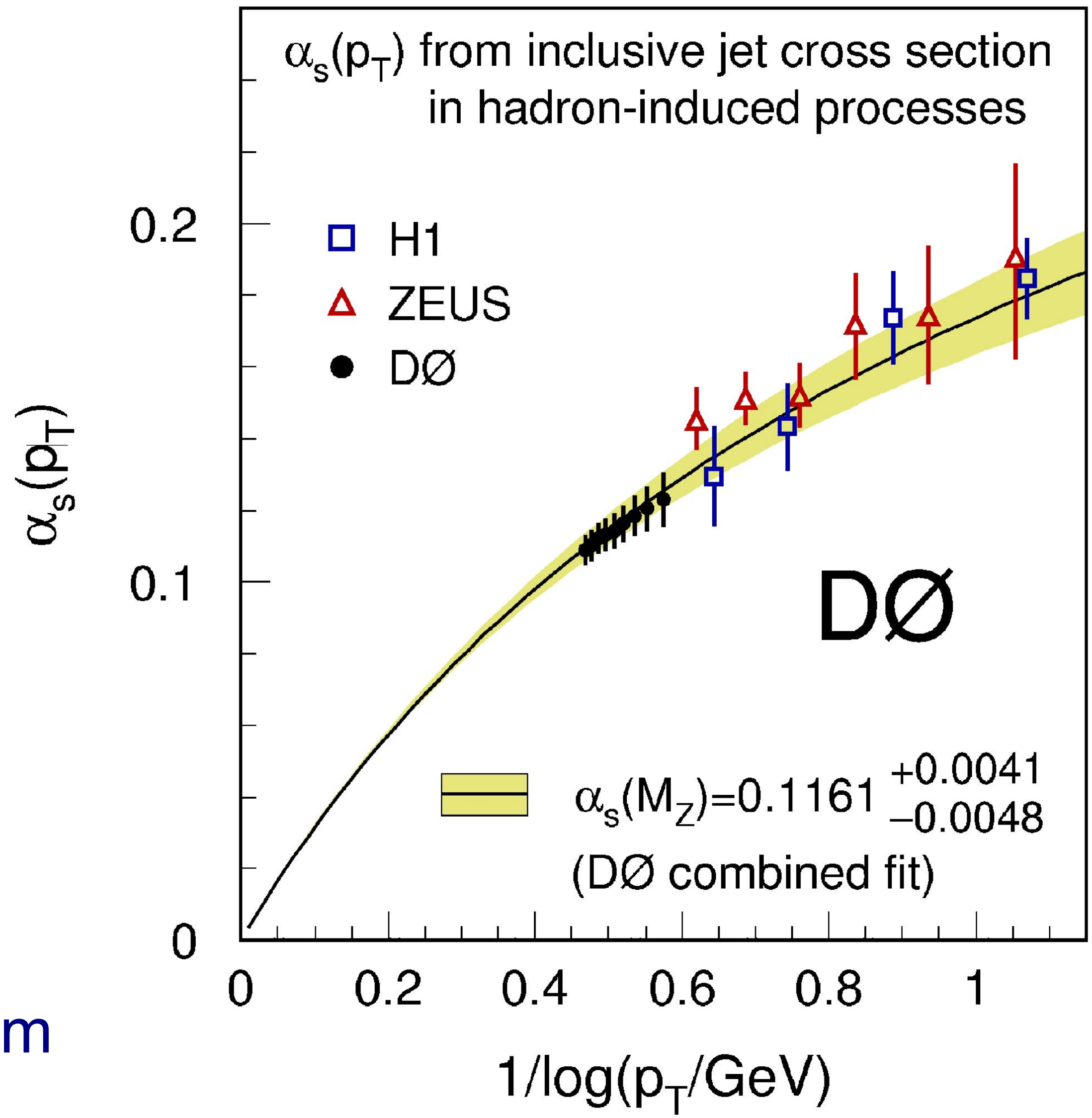
- Extends results from HERA to higher p_T

- **Highest P_T measurements of running α_s to date**



Results α_s

$\alpha_s(M_Z)$	**0.1161** +0.0041 -0.0048
exp. uncorr.	± 0.0001
exp. corr.	+ 0.0034 - 0.0029
non-perturb correction	± 0.0010
PDF uncertainty	+ 0.0012 - 0.0011
μ(r,f) variation	+ 0.0021 - 0.0029



Consistent with asymptotic freedom

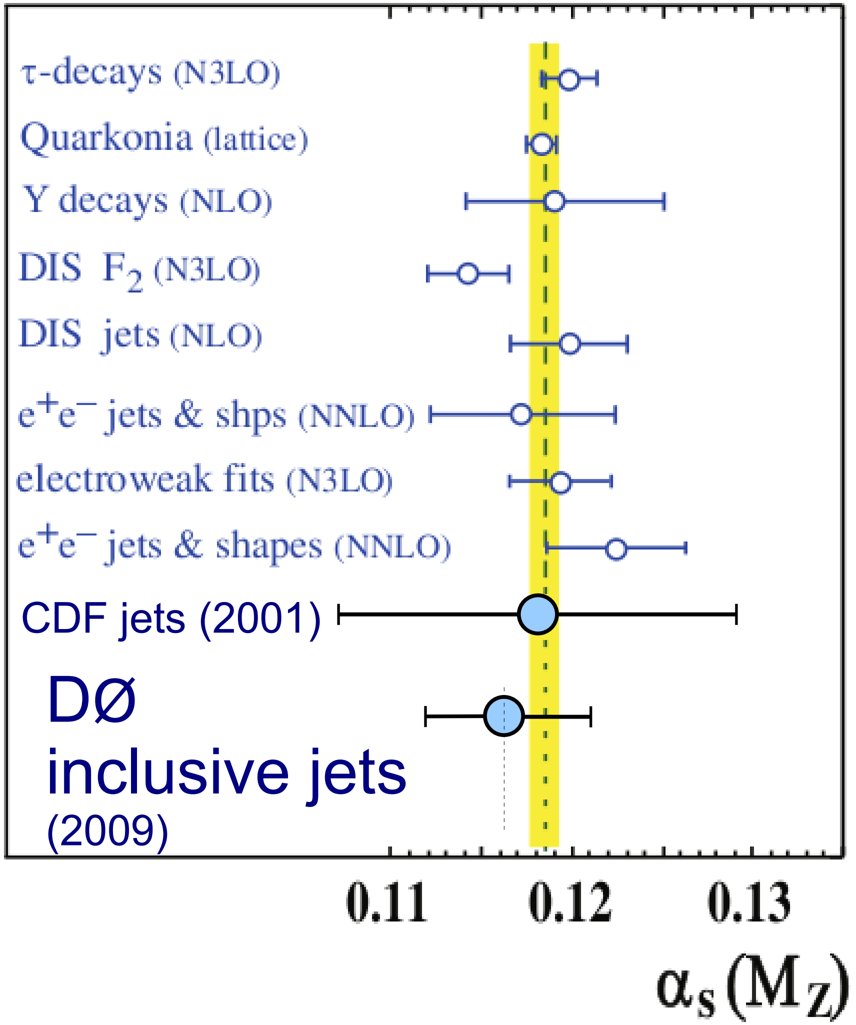
Results α_s

Have determined *alpha strong* from the DØ inclusive jet cross section

using theory at NLO plus NNLO corrections.

The measured $\alpha_s(p_T)$ supports the energy dependence predicted by the RGE.

This is the most precise determination of the strong coupling constant from a hadron collider, comparable to ep→jets.



$$\alpha_z(M_Z) = 0.1161^{+0.0048}_{-0.0041}$$

Modifed from: arXiv:0908.1135
Eur.Phys.J.C64:689-703,2009

Phys. Rev. D 80, 111107 (2009)

Remarks

Jets analyses are a strong component of DØ physics programs

- Providing fundamental insights into light (& also heavy) flavor PDFs, perturbative & nonperturbative models
- Our data will dominate high-x gluon for some time
- Providing most stringent limits on numerous NP models until LHC accumulates large data sets. Comparisons w/ benchmark measurements from Tevatron will speed validation of any new physics signatures.
- V+jets data critical to sorting out major backgrounds to much new physics.
- Many analyses (eg. V+jets, X+HF jets, photons, highest Björken-x) still statistics limited, **but only b/c of excellent understanding of detector.**

DØ and our sister CDF have lead the way in precision QCD at a hadron machine. Our data set will be 8x(or more) higher than most results here, solid foundation to begin LHC era.

Backups

D0 uses the 'Run II midpoint cone algorithm' [1]

- Cone sizes 0.5 and 0.7
- $E_{\mathrm{T,\,jet}} \geq 6$ GeV

- Seed-based algorithm, use all particles (or partons, or calorimeter towers) as seeds
  - make cone of radius $\Delta R = \sqrt{\Delta y^2 + \Delta \eta^2} < \mathcal{R}_{\mathrm{cone}}$ arond seed direction
  - proto-jet: add particles within cone in the 'E-scheme' (four-vector addition)
  - iterate until stable solution is found (cone axis = jet axis)
- Use all midpoints between jet pairs as additional seeds for infrared safety
- Combine solutions from the above two steps
  - remove identical solutions
  - remove proto-jets with $E_{\mathrm{T}} < E_{\mathrm{T,\,min}}$
- Treat jets with overlapping cones (split/merge)
  - merge jets if more than 50% of the lowest jet p_{T} is contained in the overlap
  - otherwise split jets and assign particles in overlap to nearest jet

[1] G.C. Blazey et al., Proc. of the QCD and Weak Boson Physics in Run II Workshop (Batavia 1999), [hep-ex/0005012]

Generators and Tunes

- PYTHIA, *Comp. Phys. Comm. 135, 238 (2001)* :
  - LO 2-jet Maxtrix Elements plus Parton Showers
  - Tunes:
    Field's (see arXiv:hep-ph/0610012 for details)
    - Tune A – Q^2-ordered showers, large starting scale for ISR. Fit using CDF underlying data
    - Tune DW - Q^2-ordered showers, tuned to match Z p_T-distribution, D0 dijet $\Delta\phi$ results.
    - Tune BW - Q^2-ordered showers, softer ISR than DW

    Sandhoff-Skands, et al.
    (see arXiv:hep-ph/0905.3418, and *Eur. Phys. J. C 39 (2005)* for details)
    - Tune S0 – p_T-order showers, annealing color reconnection.
      - "Professor pT0"
      - Perugia Series of Tunes – Refinements on Tune s0
    - General Area Law (GAL) – S0 tune with GAL color reconnections
- SHERPA, *JHEP 0902, 007 (2009)* :
  - Matched tree-level 2-,3-, and 4-jet Matrix Elements plus Parton Showers